CS 1680
IP Forwarding realities

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Based partly on lecture notes by Rodrigo Fonseca, David Mazières, Phil Levis, John Jannotti

Administrivia

- Look for announcement to sign up for IP milestone meetings, preferably with your mentor TA, on or before Friday (Oct 4)
  - You don't need to show an implementation, but you are expected to talk about your design

- IP gearup II: Thursday 6-8pm in CIT368
  - Implementation and debugging tips

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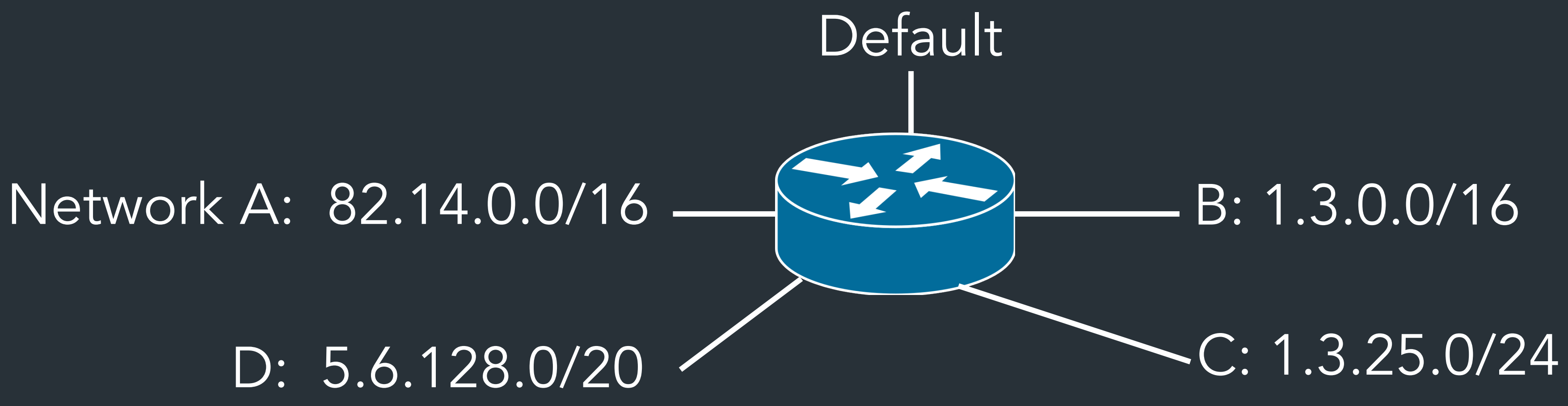
- IP gearup II: Thursday 6-8pm in CIT368
  - Implementation and debugging tips
- HW1: Due Thursday (HW2 out Thursday)

Today

Odds and ends that make IP forwarding actually work

- Longest Prefix Match
- IP<->Link layer (ARP, DHCP)
- Network Address Translation (NAT)

After this: Routing



Prefix	IF/Next hop
82.14.0.0/16	(A)
1.3.0.0/16	(B)
1.3.4.0/24	(C)
5.6.128.0/20	(D)
0.0.0.0/0	(Default)

(X) is placeholder—could be an IP or an interface name

Warmup: based on the table, where would the router send packets destined for the following addresses:

1. 5.6.128.100
2. 1.3.1.1
3. 8.8.8.8
4. 1.3.4.8

What happens when prefixes overlap?

Prefix	IF/Next hop
1.3.0.0/16	(B)
1.3.4.0/24	(C)
1.3.4.5/32	
0.0.0.0/0	(Default)

An IP can match on more than one row
=> need to pick the most specific (longest) prefix

1.3.0.0/16	00000001 00000011 xxxxxxxx xxxxxxxx
1.3.4.0/24	00000001 00000011 00000100 xxxxxxxx

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```

More specific => best match!

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1.3.0.0/16 00000001 00000011 xxxxxxxx xxxxxxxx

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More specific => best match!

Other examples you'll see…

0.0.0.0/0 xxxxxxxx xxxxxxxx xxxxxxxx xxxxxxxx

1.2.3.5/32 00000001 00000011 00000100 00000101

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1.3.4.5/32	
0.0.0.0/0	(Default)

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Other examples you'll see…

0.0.0.0/0 xxxxxxxx xxxxxxxx xxxxxxxx xxxxxxxx => Least specific!
(Used for default "catchall" routes)

1.2.3.5/32 00000001 00000011 00000100 00000101 => Most specific!
(Refers to a single host, often a local IP)

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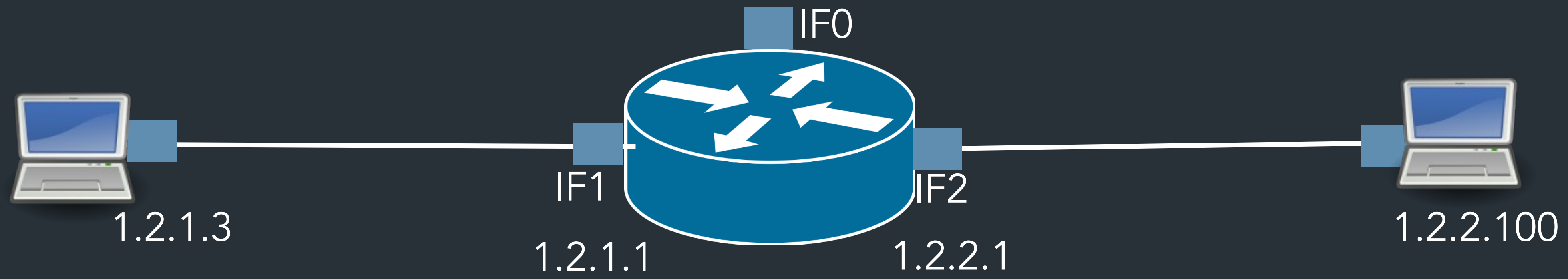
=><u>Longest prefix matching</u>: can keep forwarding tables small by summarizing routes where possible, otherwise using specific prefixes

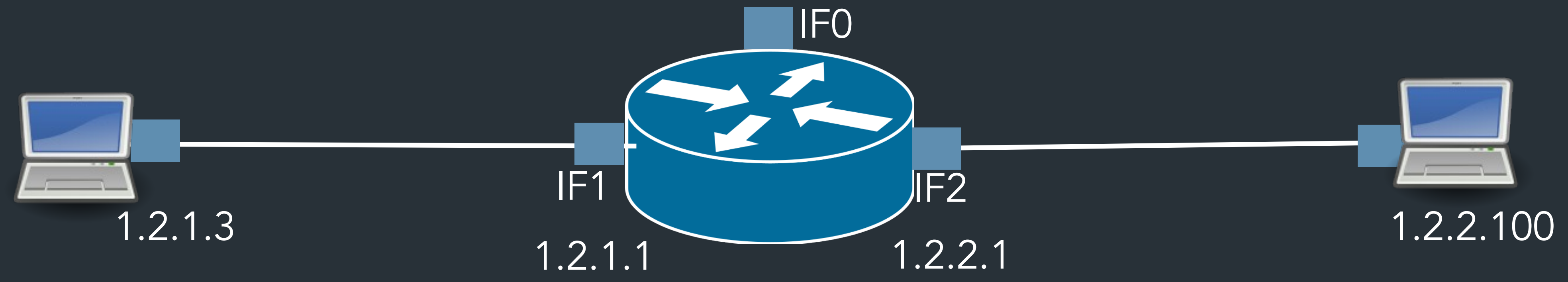
What happens at the link layer?



What does it mean to send to IF1?

Prefix	IF/Next hop
1.2.1.0/24	IF1
1.2.2.0/24	IF2
8.0.0.0/30	IF0
Default	8.0.0.2

What happens at the link layer?

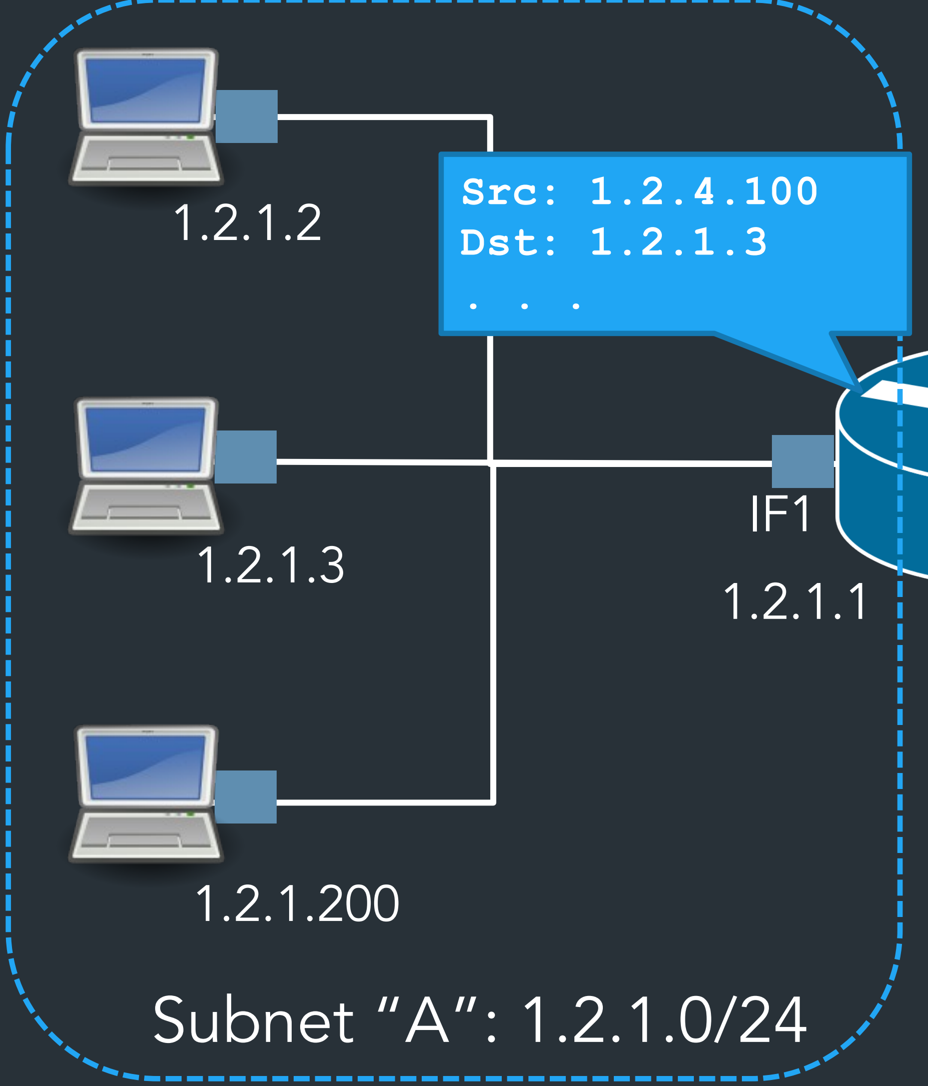


What does it mean to send to IF1?

The story so far:
=>Can "easily" communicate with nodes on the same network,
but what about other networks?
=> Routers know about multiple networks, forward packets between them

Prefix	IF/Next hop
1.2.1.0/24	IF1
1.2.2.0/24	IF2
8.0.0.0/30	IF0
Default	8.0.0.2

"Local delivery": what does it mean to send to IF1?



Prefix	IF/Next hop
1.2.1.0/24	IF1
…	…

"Local delivery": what does it mean to send to IF1?

So far: "easy" to communicate with nodes on the same network. But how?

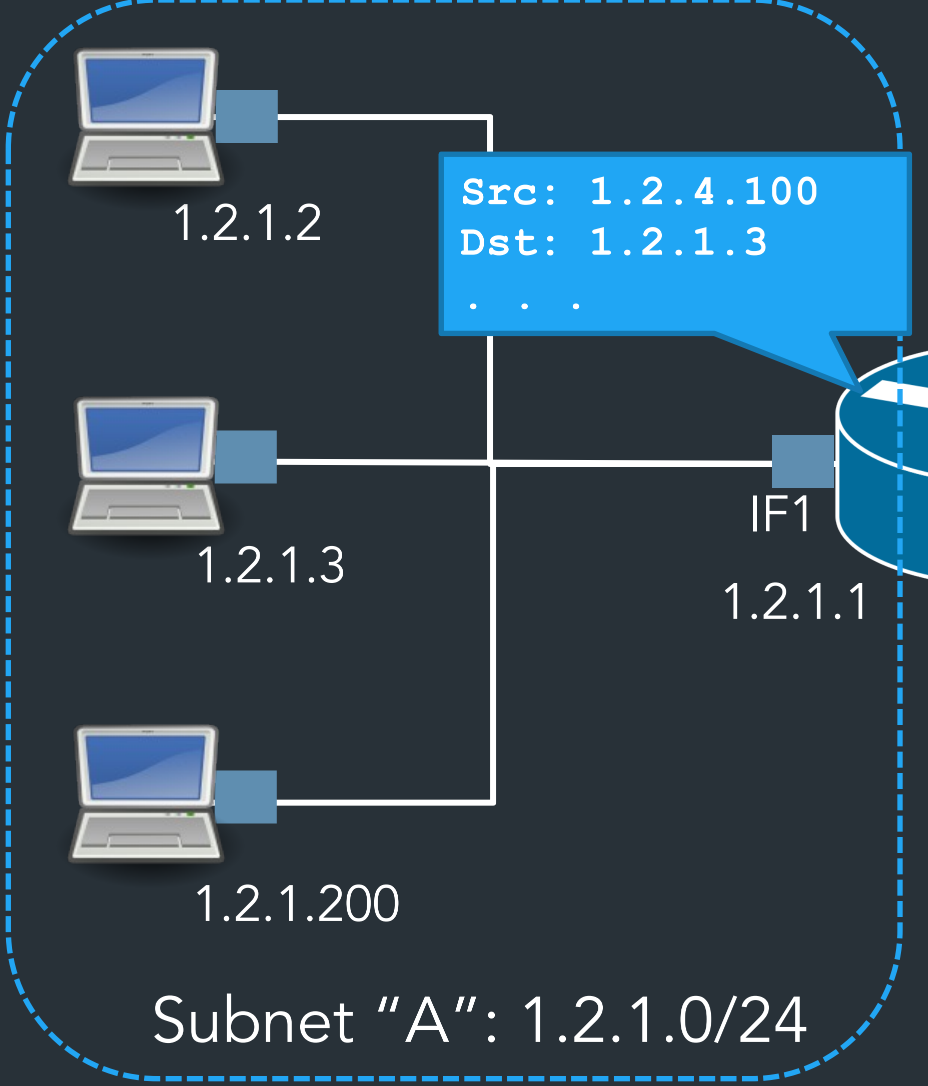
To send a packet on a local network, we need:

- Dest. IP (Network layer)
- Dest. MAC address (Link layer)

	Src	Dest
Link		???
IP	10.2.4.100	1.2.1.3

Assume: link layer can figure out the rest once we fill in this info

=> How do we get the MAC address?



Prefix	IF/Next hop
1.2.1.0/24	IF1
…	…

“Glue” between L2 and L3

Need a way to connect get link layer info (mac address) from network-layer info (IP address)

“What MAC address has IP 1.2.3.4?”

“Glue” between L2 and L3

Need a way to connect get link layer info (mac address) from network-layer info (IP address)

“What MAC address has IP 1.2.3.4?”

Solution: ask the network!
=> Address Resolution Protocol (ARP)

ARP: Address resolution protocol

Given an IP address, ask network for the MAC address

- Request: "`Who has 1.2.3.4?`"
- Response: "`aa:bb:cc:dd:ee:ff is at 1.2.3.4`"

How ARP works

ARP: Address resolution protocol

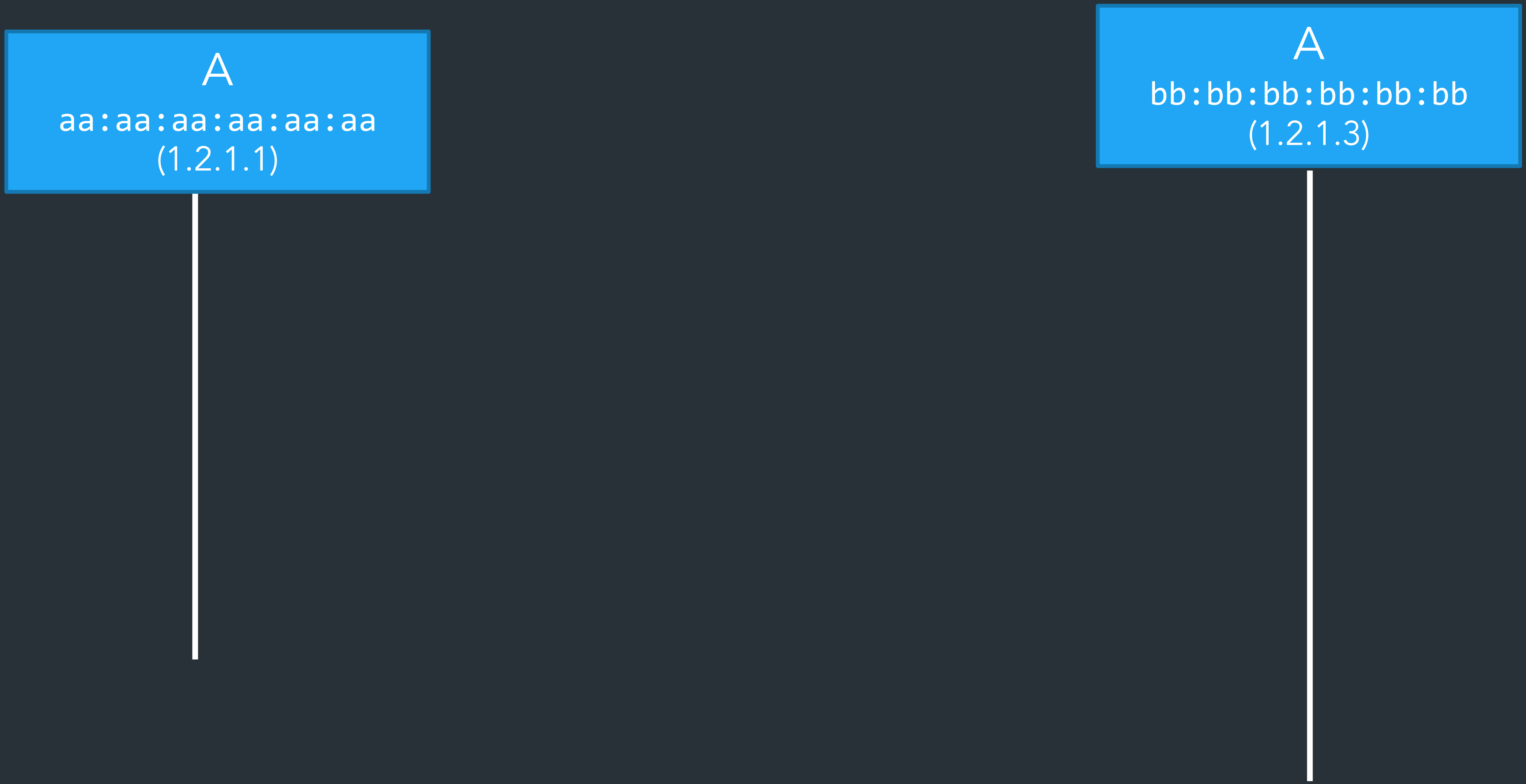
Given an IP address, ask network for the MAC address

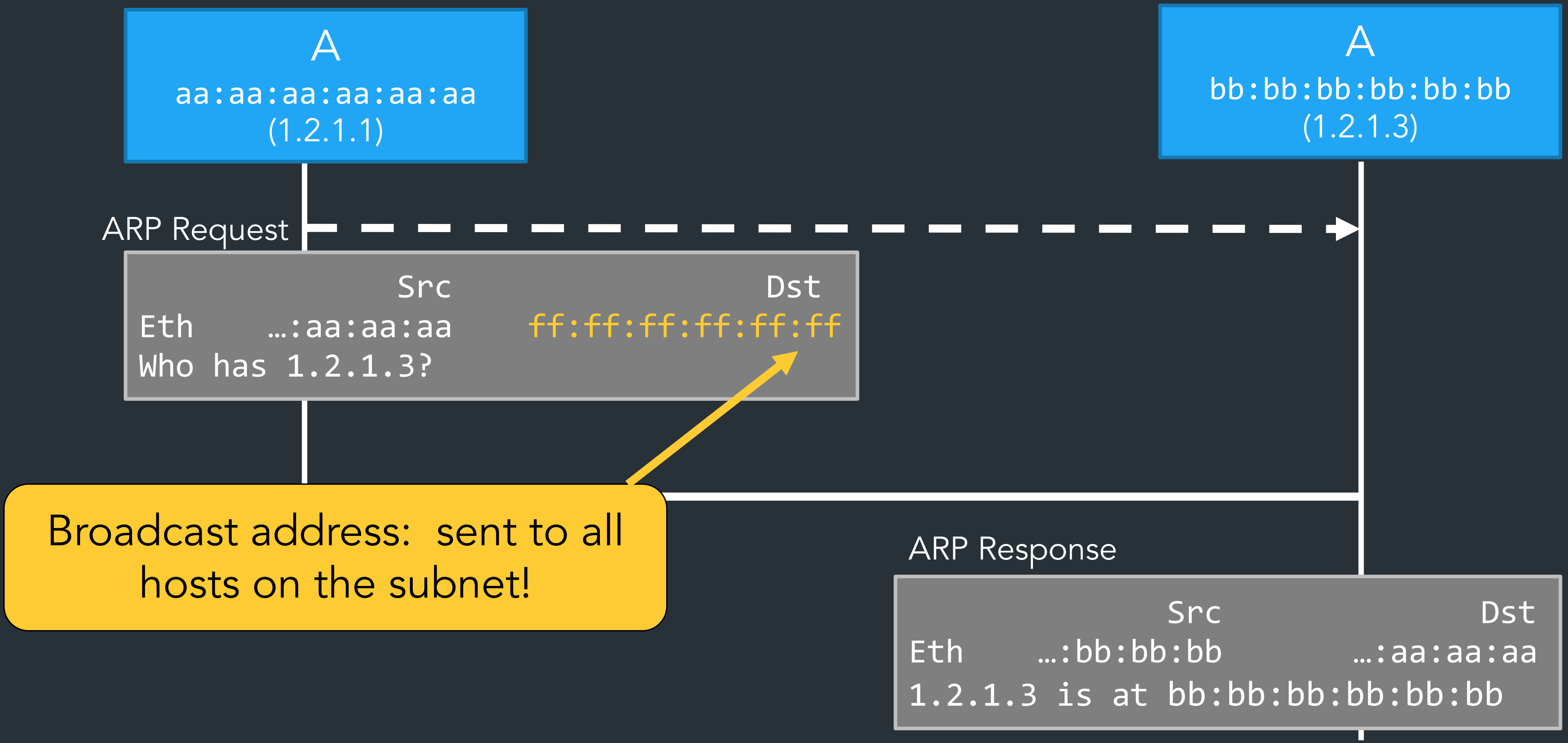
Request: "`Who has 1.2.3.4?`"

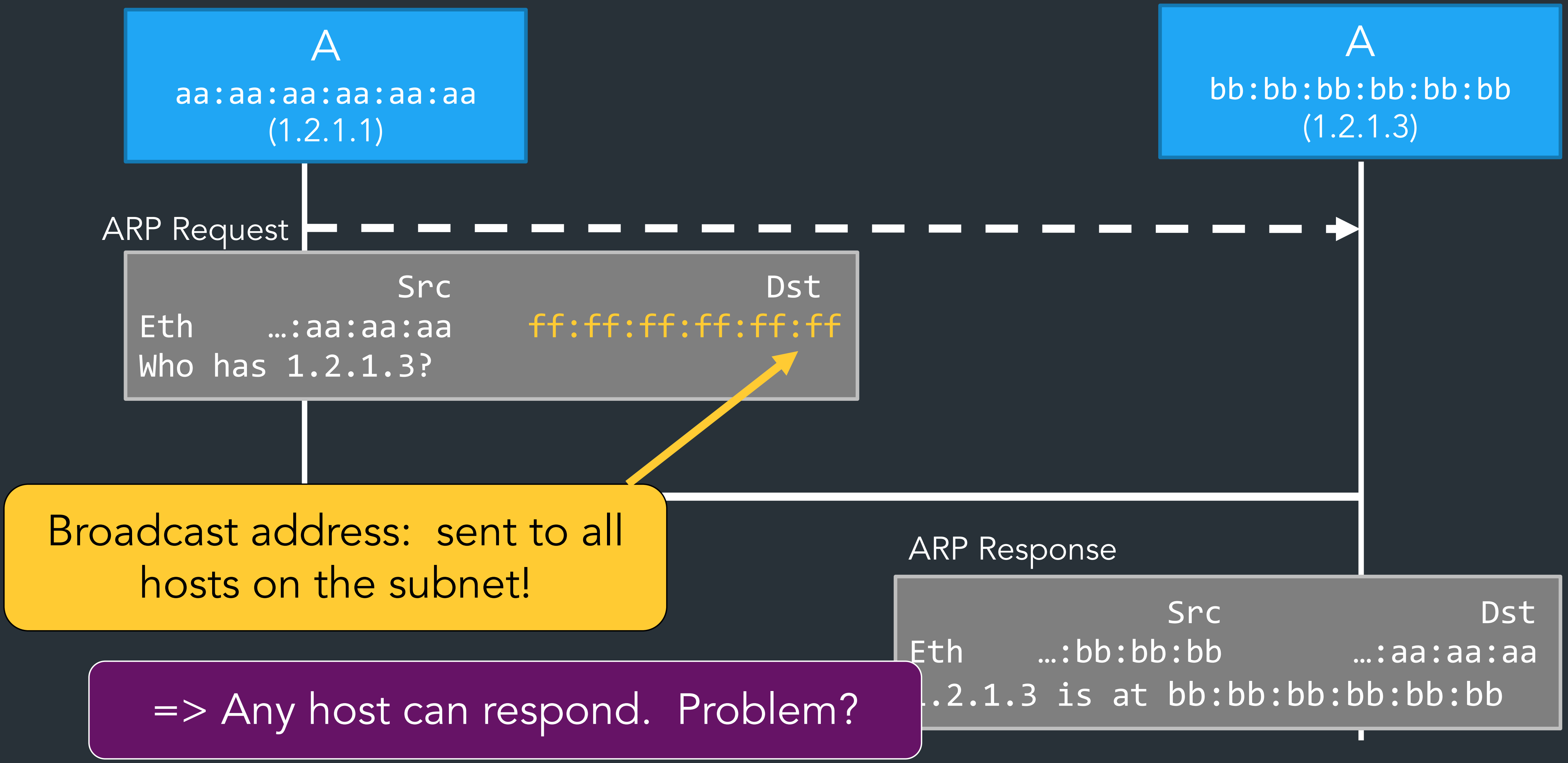
Response: "`aa:bb:cc:dd:ee:ff is at 1.2.3.4`"

Key data structure: ARP table: map of IP -> MAC address

- All devices use ARP protocol to build their own table
- Requests send to *broadcast address*: `ff:ff:ff:ff:ff:ff`


A
aa:aa:aa:aa:aa:aa
(1.2.1.1)
A
bb:bb:bb:bb:bb:bb
(1.2.1.3)


A
aa:aa:aa:aa:aa:aa
(1.2.1.1)
A
bb:bb:bb:bb:bb:bb
(1.2.1.3)
ARP Request
Src
Dst
Eth
…:aa:aa:aa
ff:ff:ff:ff:ff:ff
Who has 1.2.1.3?
Broadcast address: sent to all hosts on the subnet!
ARP Response
Src
Dst
Eth
…:bb:bb:bb
…:aa:aa:aa
1.2.1.3 is at bb:bb:bb:bb:bb:bb


A
aa:aa:aa:aa:aa:aa
(1.2.1.1)
A
bb:bb:bb:bb:bb:bb
(1.2.1.3)
ARP Request
Src
Dst
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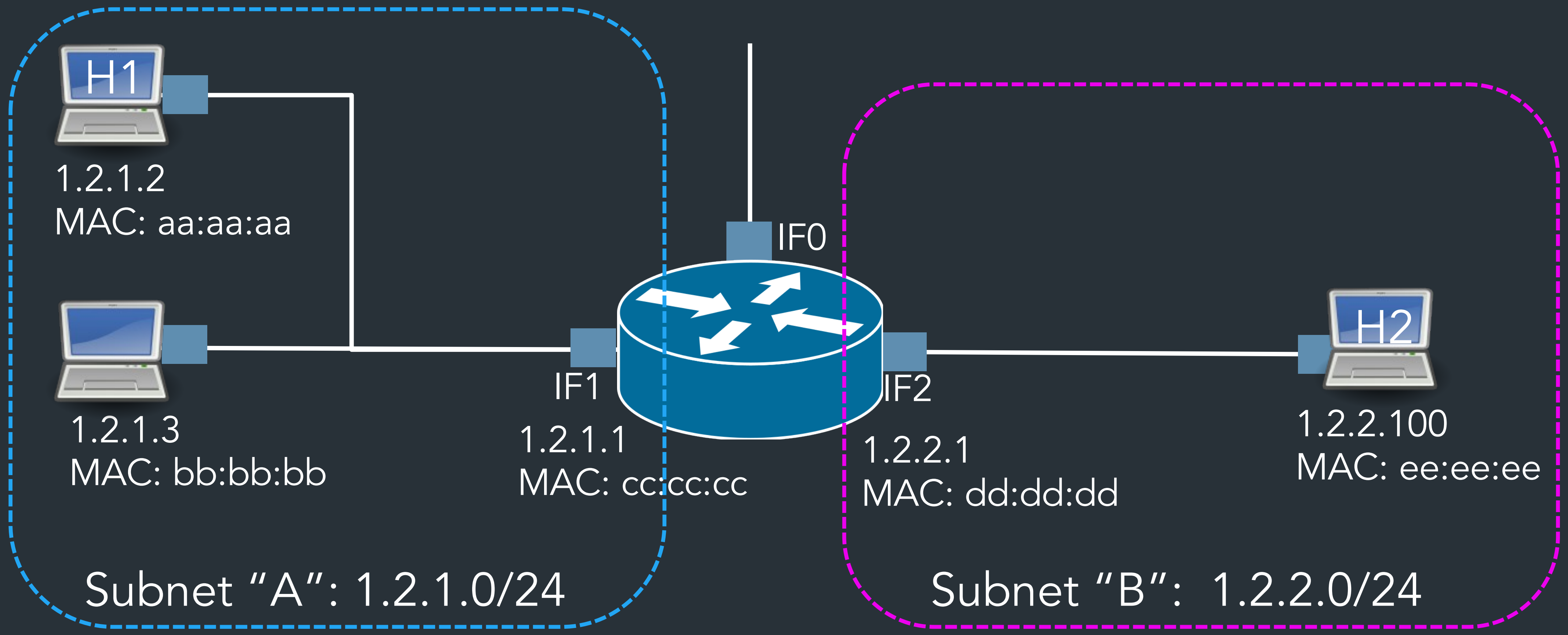
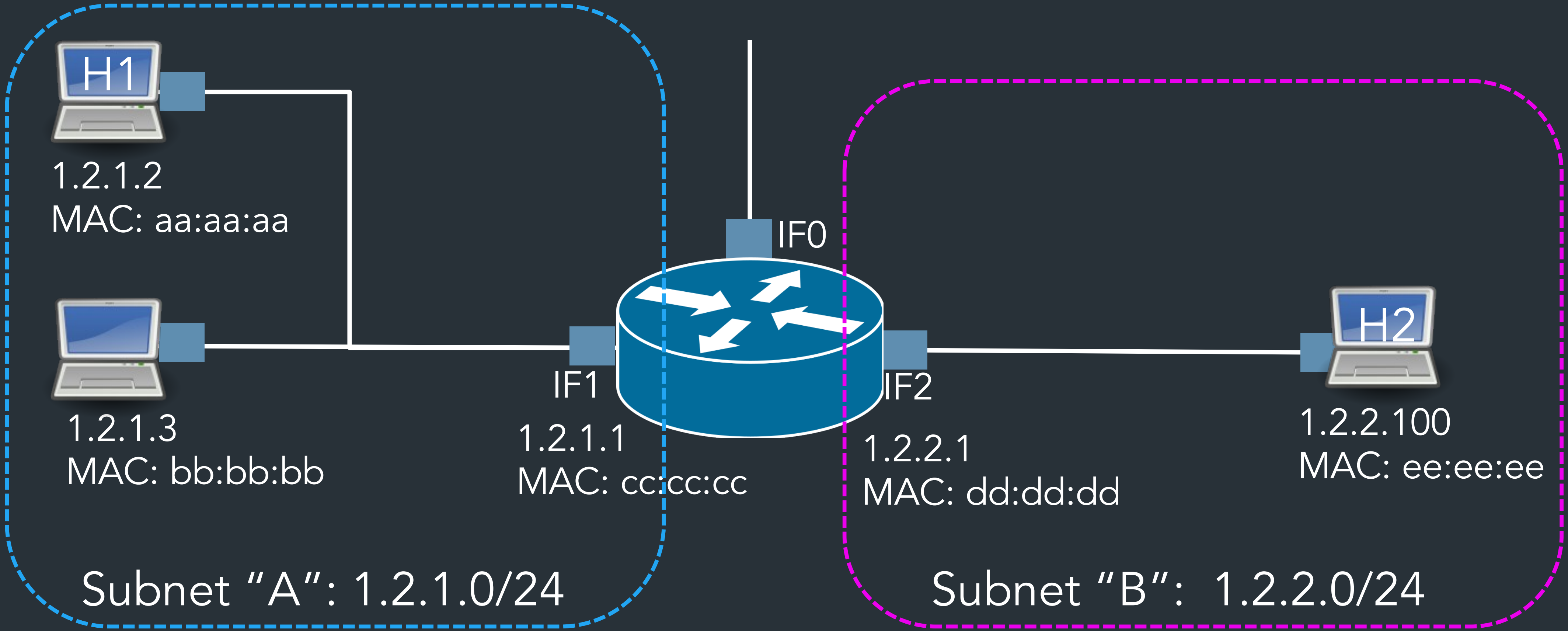
Who has 1.2.1.3?
Broadcast address: sent to all hosts on the subnet!
ARP Response
Src
Dst
Eth
…:bb:bb:bb
…:aa:aa:aa
.2.1.3 is at bb:bb:bb:bb:bb:bb
=> Any host can respond. Problem?

Example

```
# arp -n
Address                  HWtype  HWaddress           Flags Mask            Iface
172.17.44.1              ether   00:12:80:01:34:55   C                     eth0
172.17.44.25             ether   10:dd:b1:89:d5:f3   C                     eth0
172.17.44.6              ether   b8:27:eb:55:c3:45   C                     eth0
172.17.44.5              ether   00:1b:21:22:e0:22   C                     eth0
```

Putting it all together….


H1
1.2.1.2
MAC: aa:aa:aa
1.2.1.3
MAC: bb:bb:bb
IF0
IF1
1.2.1.1
MAC: cc:cc:cc
IF2
1.2.2.1
MAC: dd:dd:dd
H2
1.2.2.100
MAC: ee:ee:ee
Subnet "A": 1.2.1.0/24
Subnet "B": 1.2.2.0/24

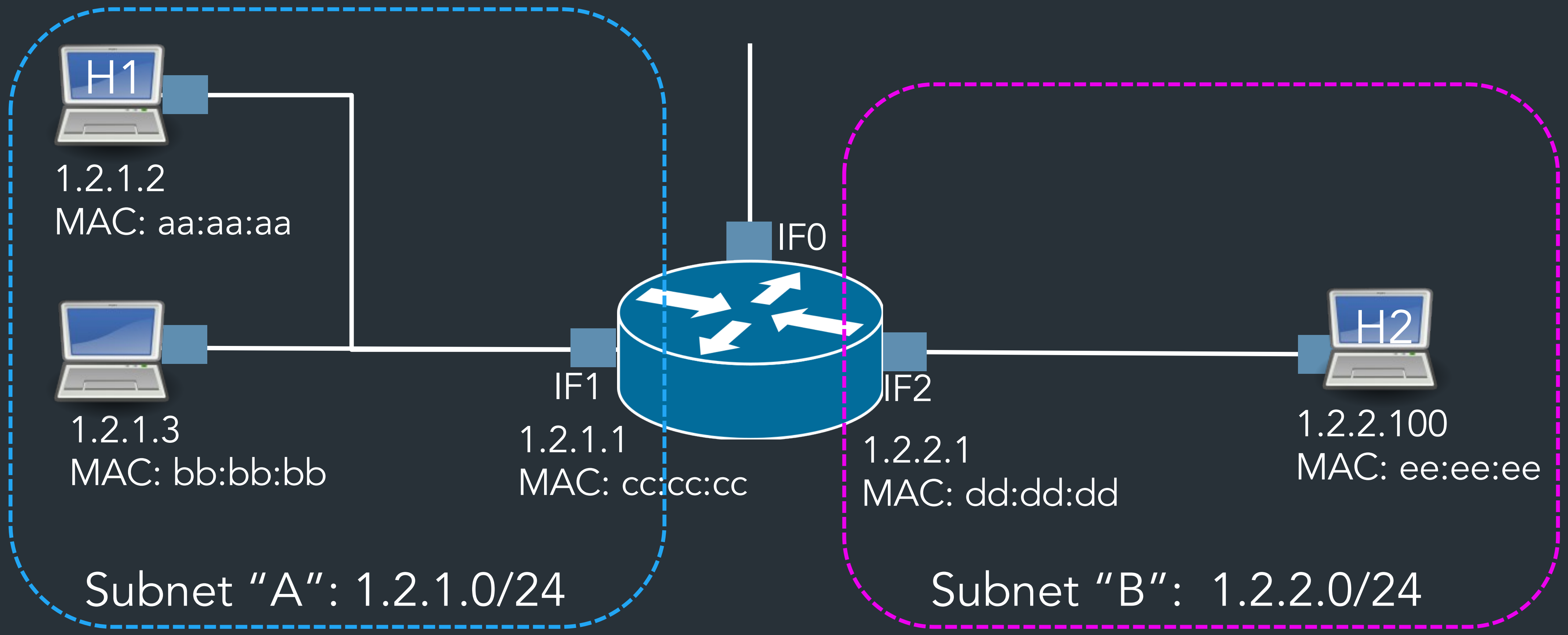


Suppose H1 wants to send a packet to H2.

Q: What would the headers look like when the packet leaves H1?

Q: Would it change after reaching R?

	Src	Dest
Link		
IP		



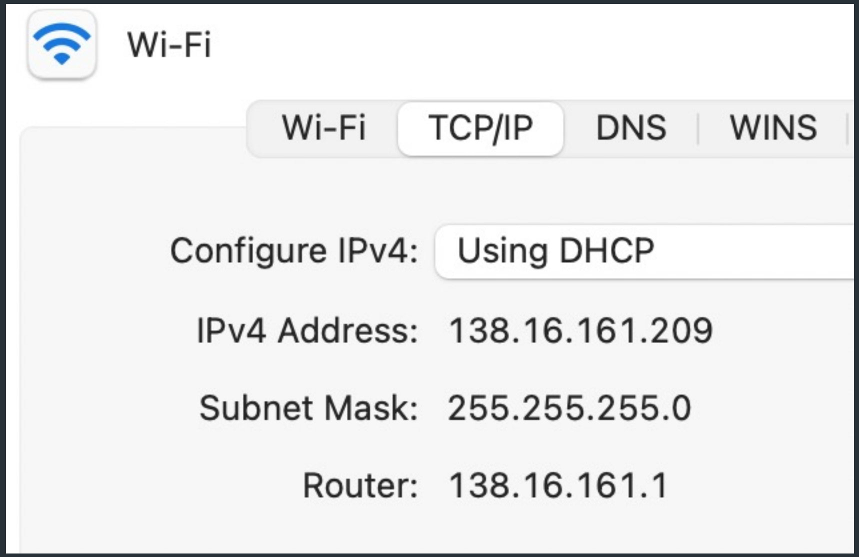
H1's forwarding table

Prefix	IF/Next hop
1.2.1.0/24	IF0
0.0.0.0/0	1.2.1.1

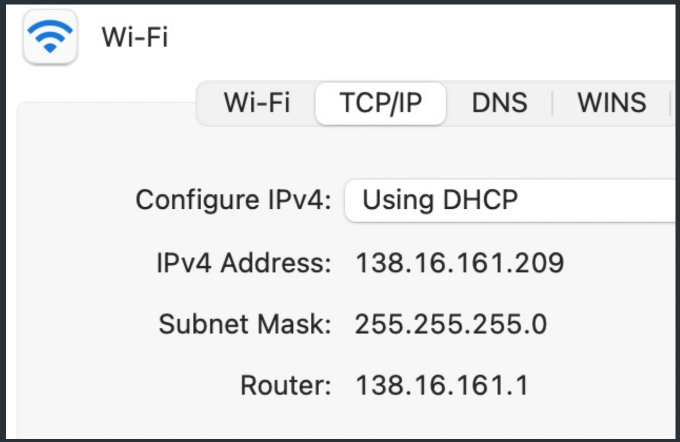
Router's forwarding table

Prefix	IF/Next hop
1.2.1.0/24	IF1
1.2.2.0/24	IF2

How do you get an IP address?



Getting an IP



Two ways to configure an IP for a host:

- Static configuration: manually specify IP address, mask, gateway, …
- Automatic: ask the network for an IP when you connect!

Getting an IP

Two ways to configure an IP for a host:

- Static configuration: manually specify IP address, mask, gateway, …

  => More common with network devices that don't change often

- Automatic: ask the network for an IP when you connect!

  => Most common for end hosts

  => Dynamic Host Configuration Protocol (DHCP)

DHCP: The idea

Dynamic Host Configuration Protocol

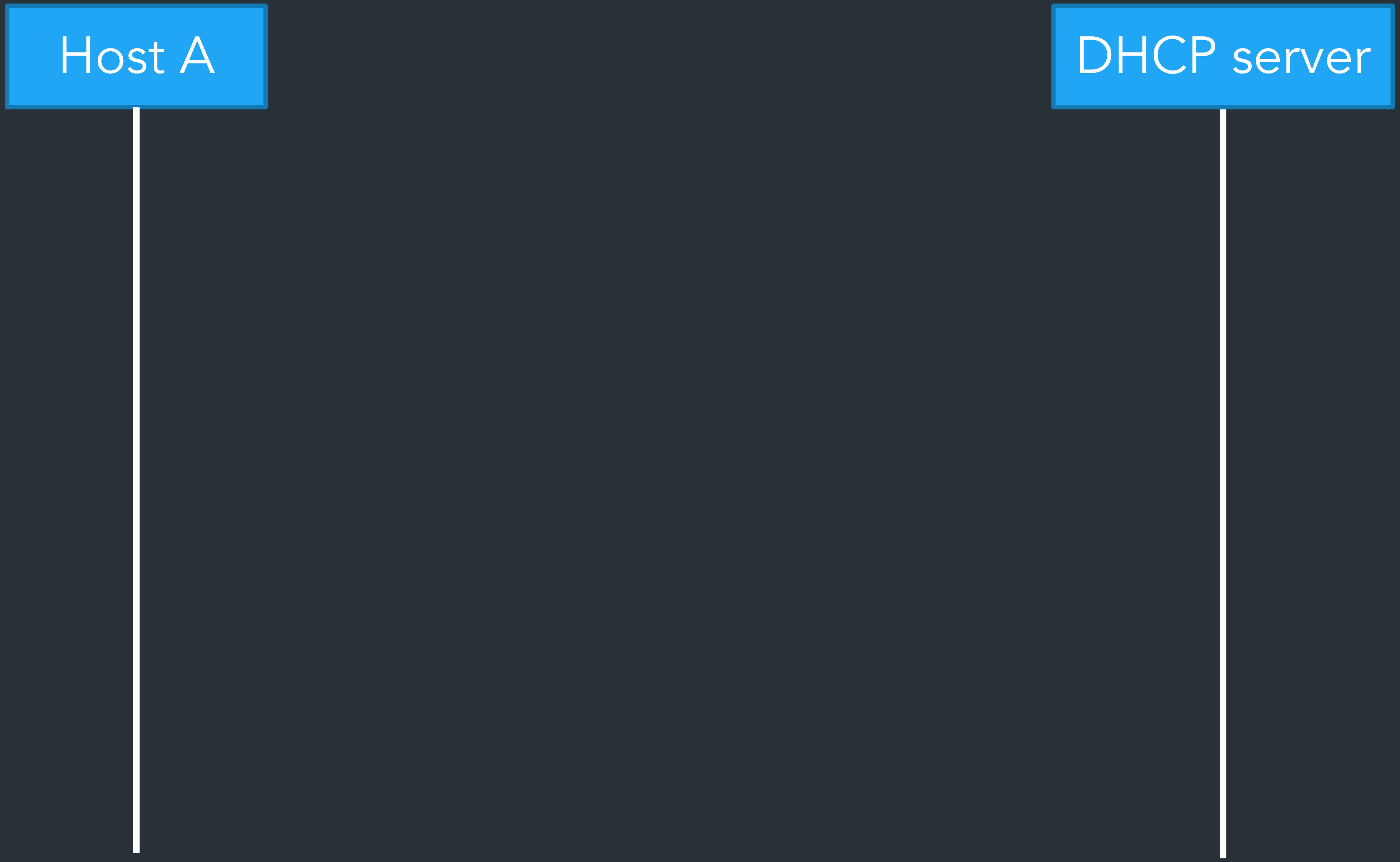
DHCP: The idea

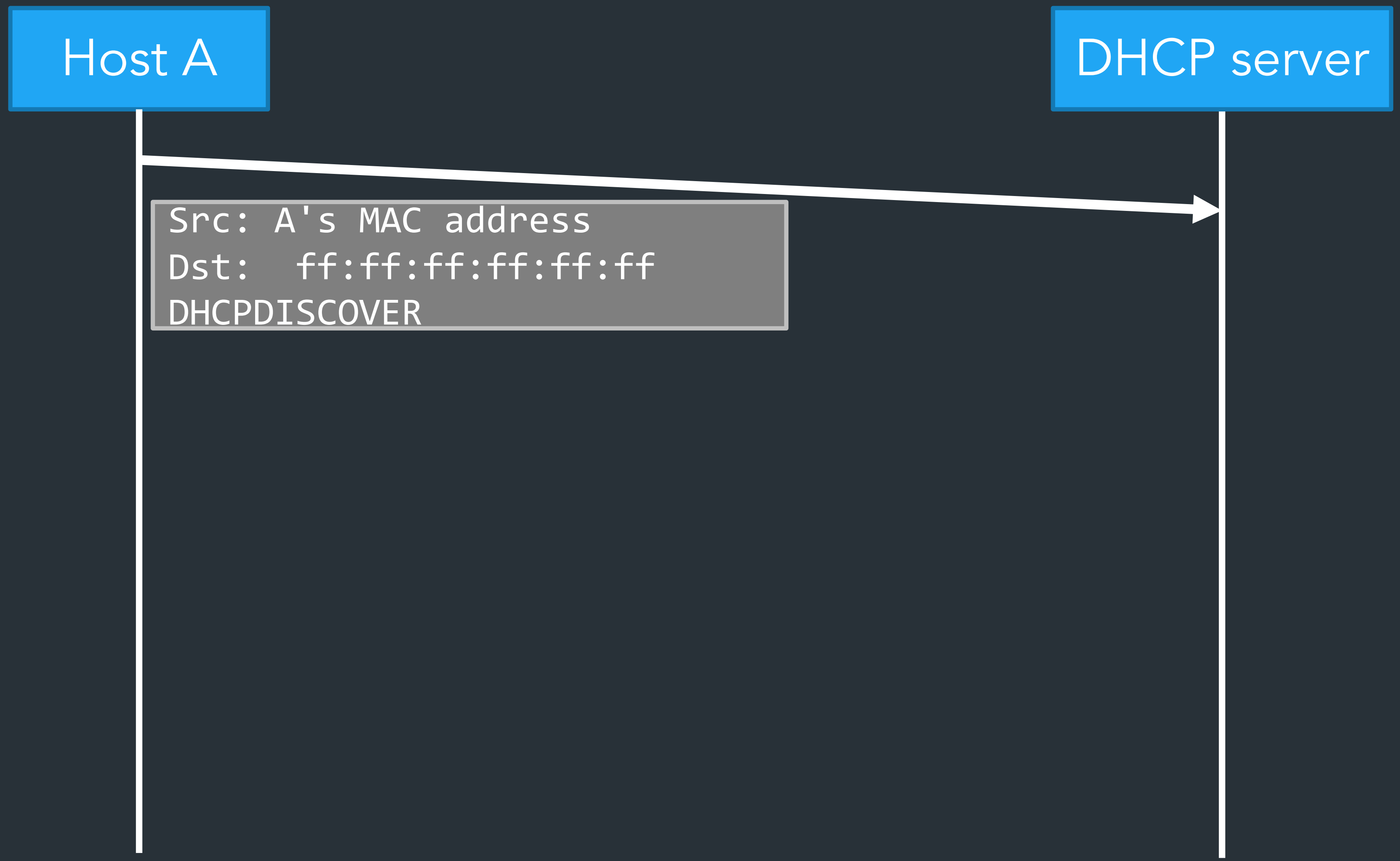
Dynamic Host Configuration Protocol

- Every network has a “pool” of IPs it can assign to hosts
  - Some subset of its prefix (eg. 192.168.1.0/24)

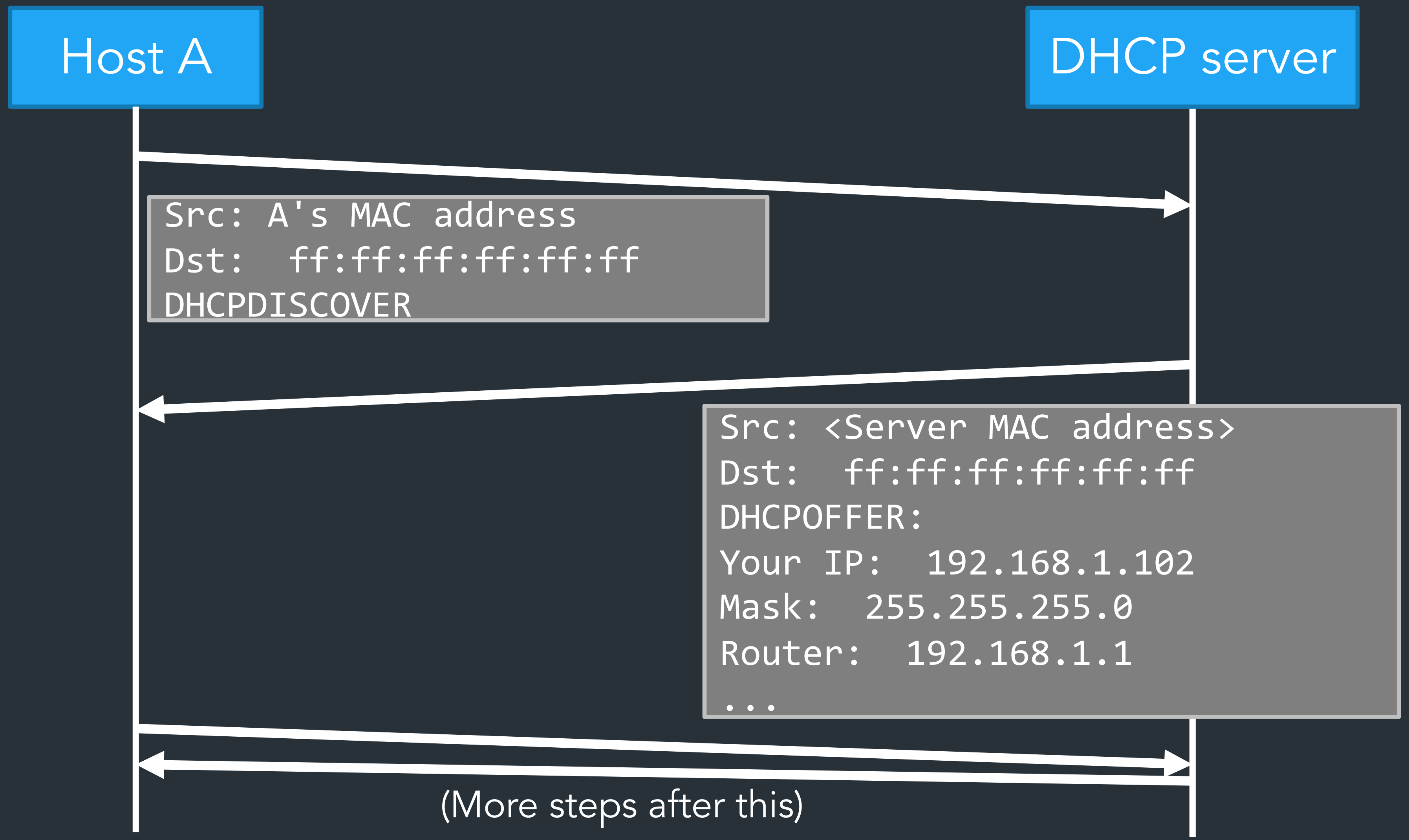
- When a host connects, it asks a DHCP server for an address from the pool

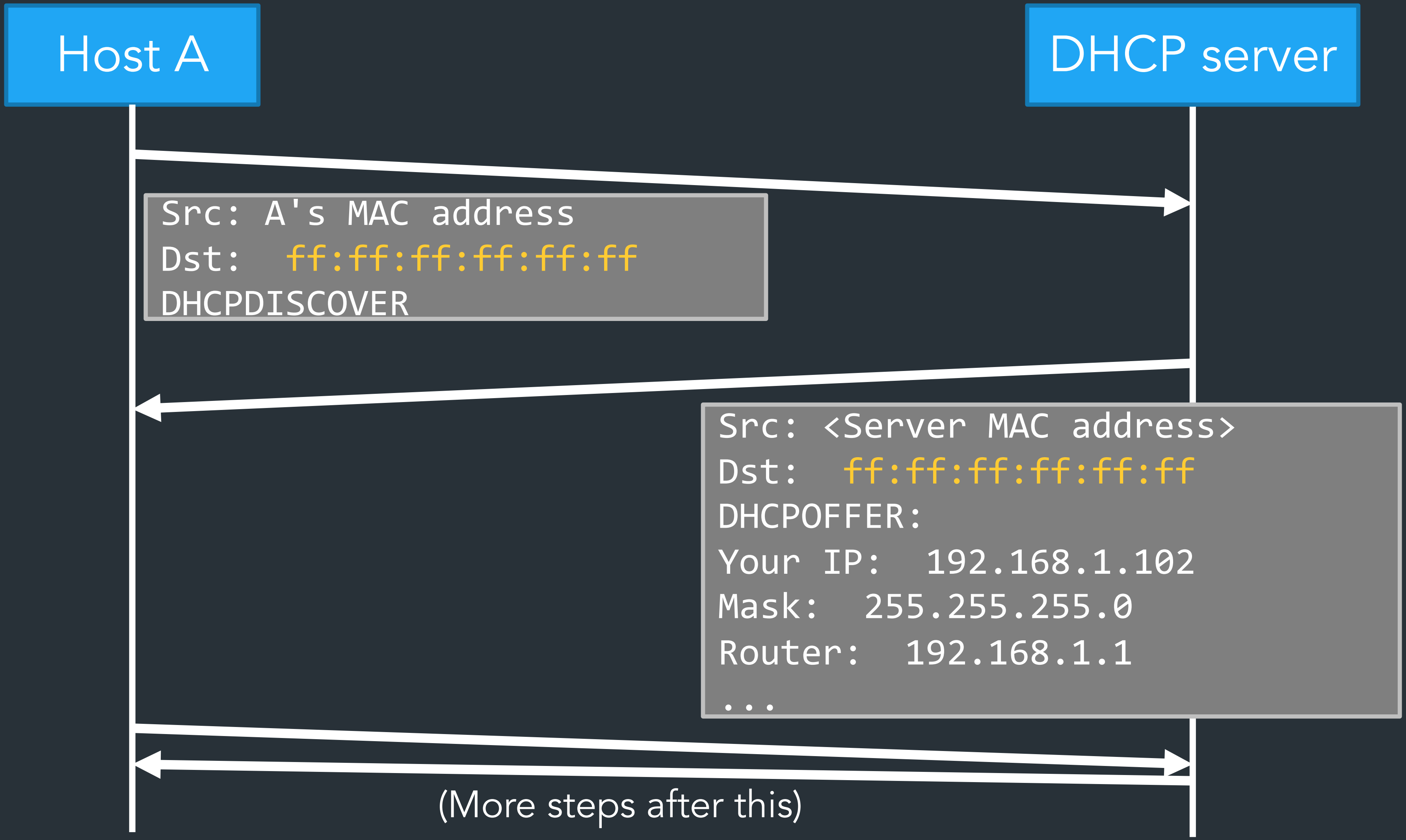
- DHCP server(s) act like allocators: give “leases” to IPs, provide other config info


Host A
DHCP server



=> Again, host needs to use broadcast address. Why?
=> Problem?


Host A
DHCP server
Src: A's MAC address
Dst: ff:ff:ff:ff:ff:ff
DHCPDISCOVER
Src: <Server MAC address>
Dst: ff:ff:ff:ff:ff:ff
DHCPOFFER:
Your IP: 192.168.1.102
Mask: 255.255.255.0
Router: 192.168.1.1
...
(More steps after this)



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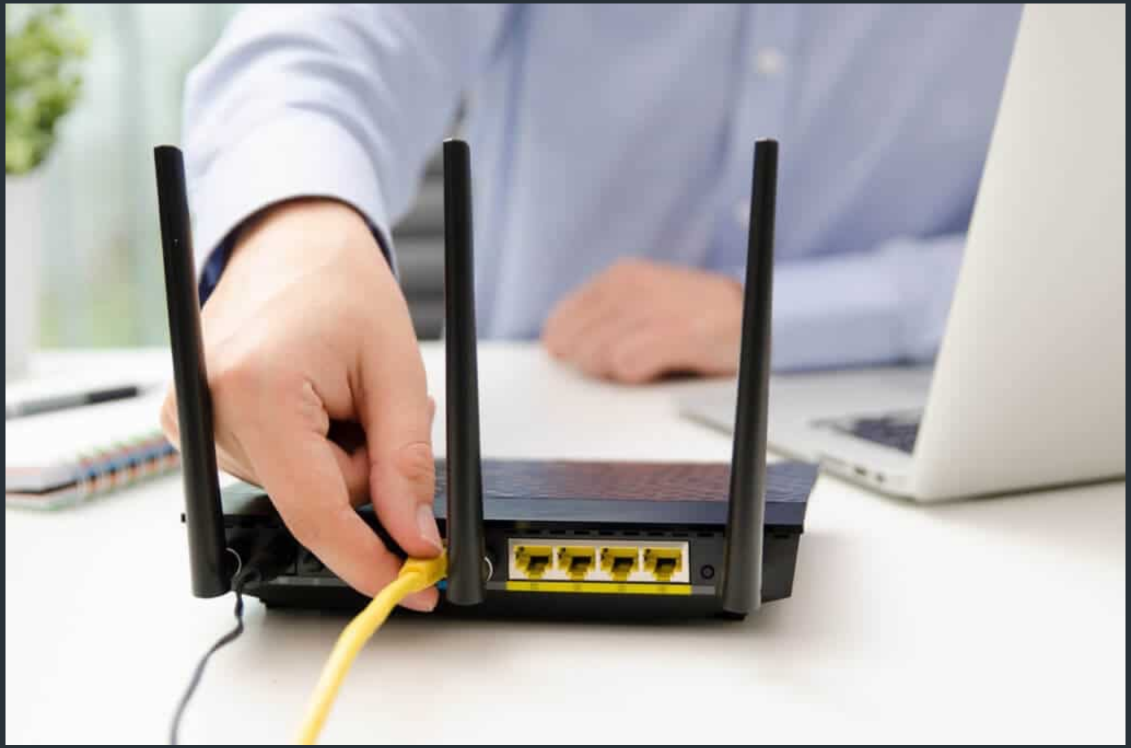
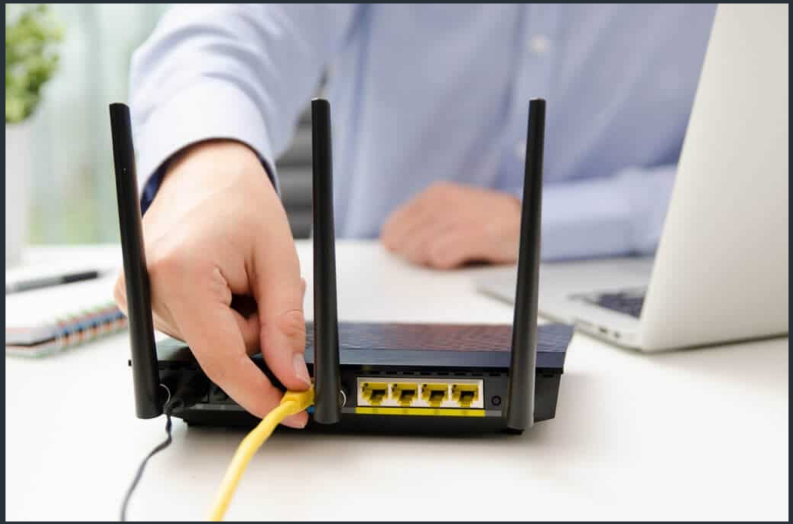


Home routers

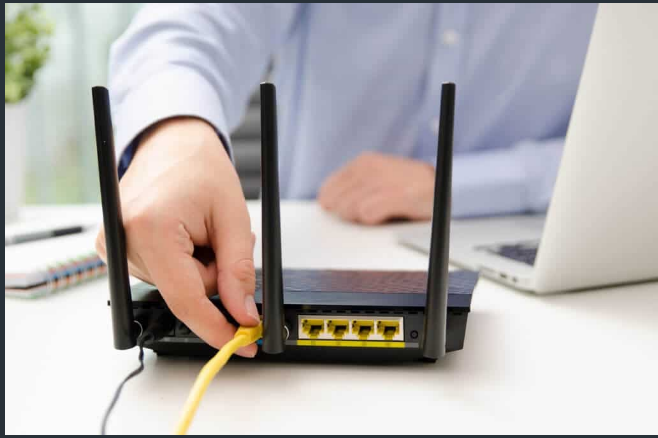
The good, the bad, and the ugly…

What’s in a home router?



Story time

Where it gets weird…



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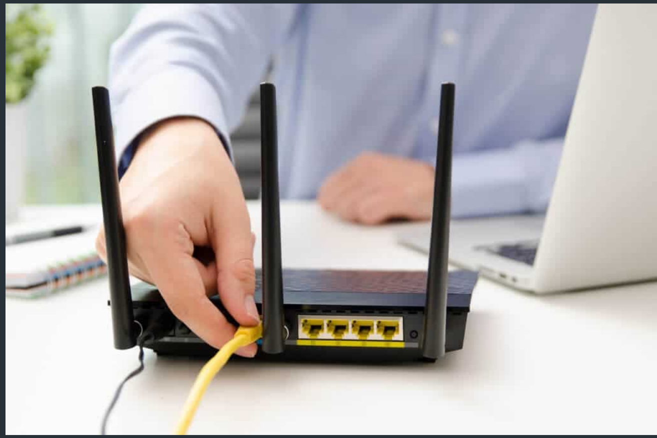

You get just one IP from your ISP...

=> Need to share IP among many devices on the same network!

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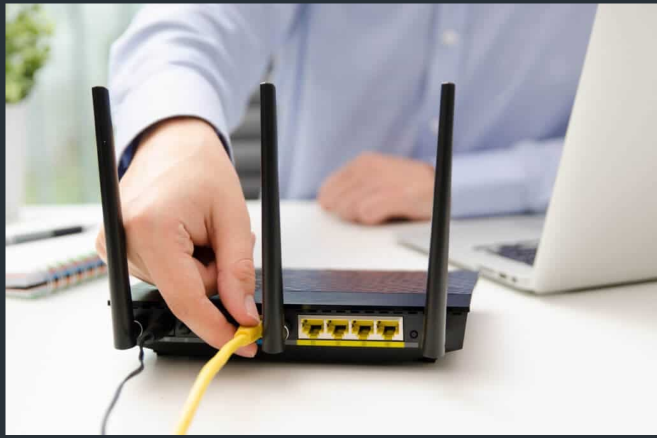


You get just one IP from your ISP…

=> Need to share IP among many devices on the same network!

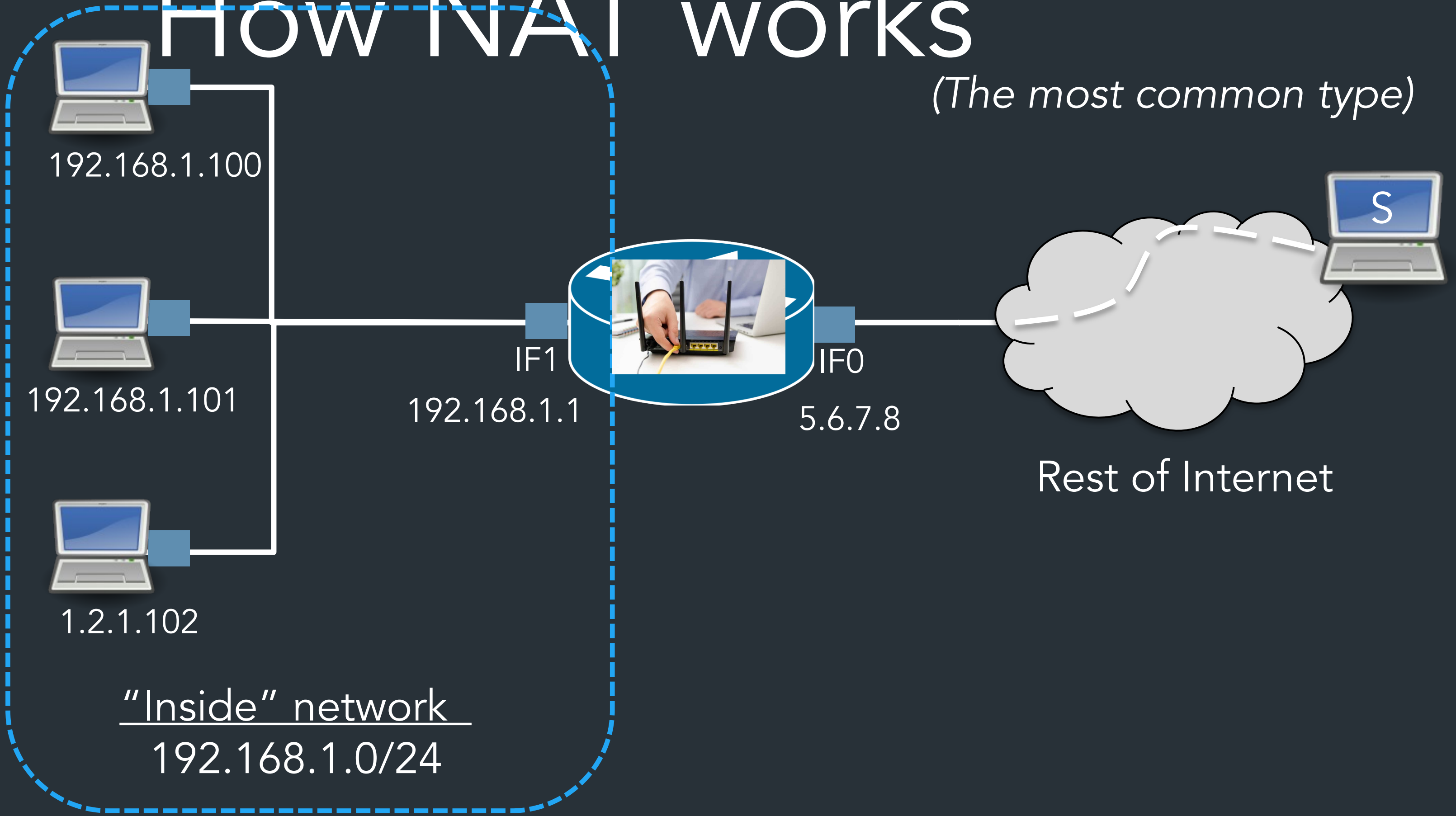
Solution: Create a "private" IP range used within local network

=> Routers need to do extra work to share public IP among many private IPs

=> Network Address Translation (NAT)
(A form of connection multiplexing)

How NAT works

(The most common type)



Goal: Share one IP among many hosts on a private network

Router *translates (modifies) packets from "inside" to use "outside" address*

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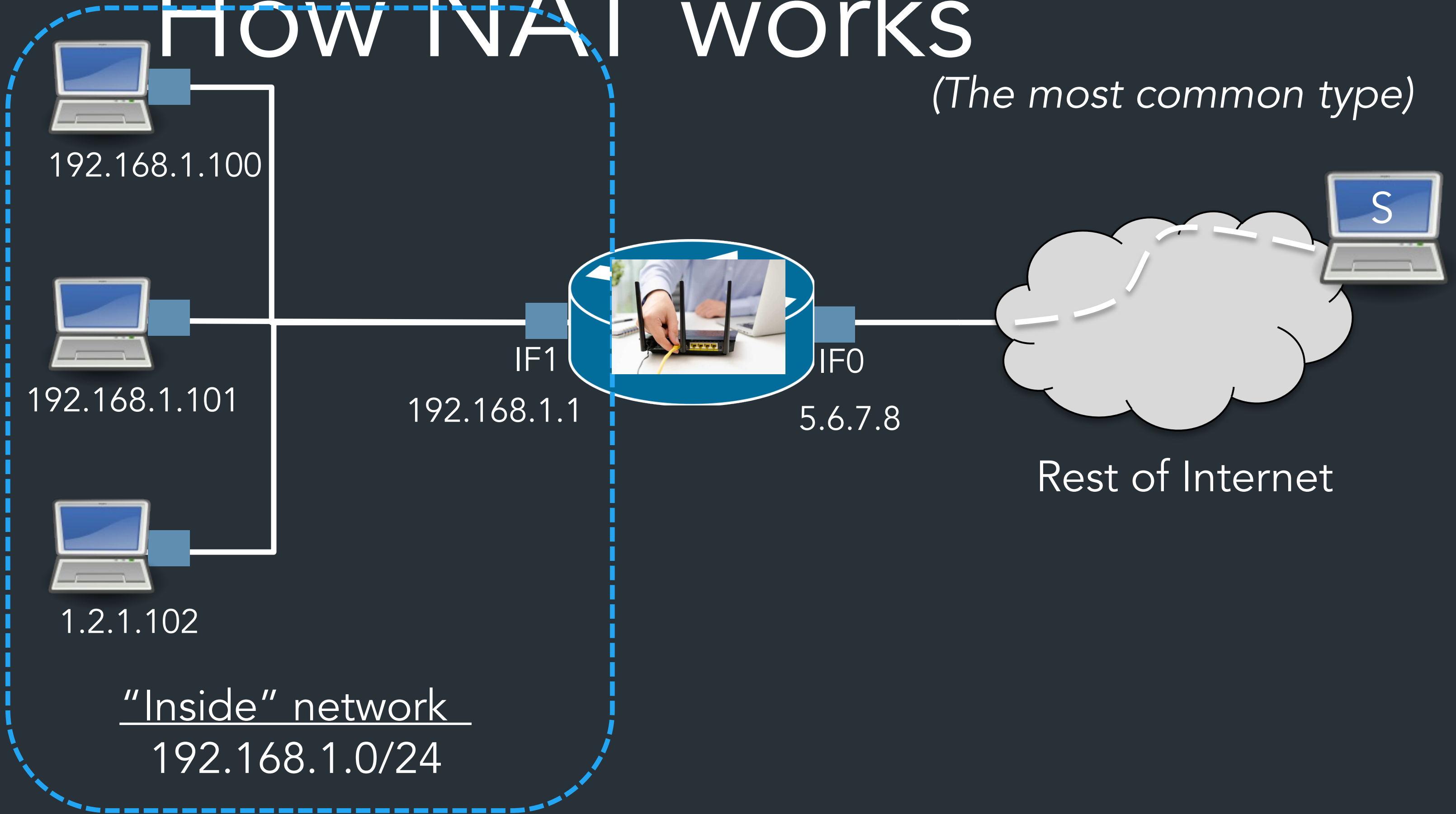


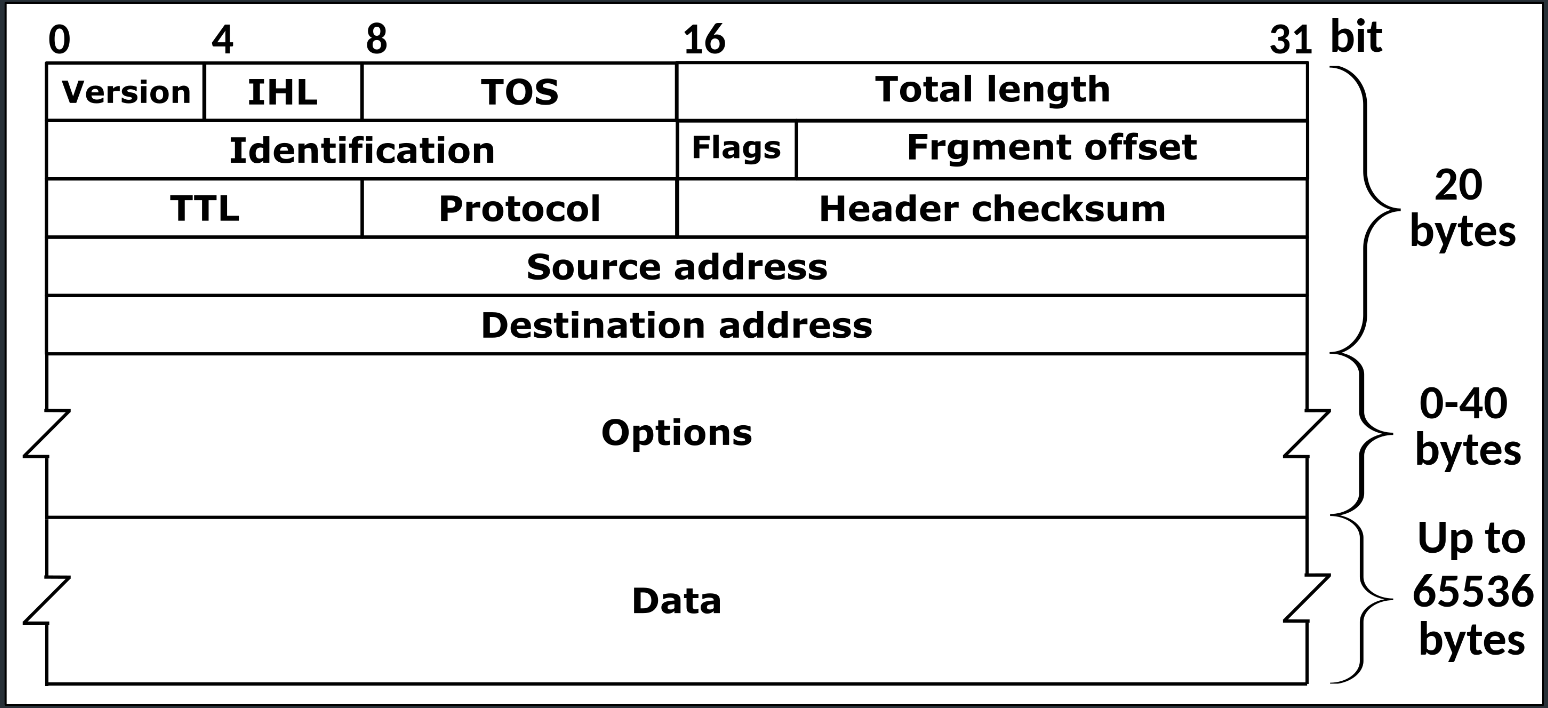
Goal: Share one IP among many hosts on a private network

Router *translates (modifies) packets from "inside" to use "outside" address*

=> Router needs to remember connection state

=> Router makes some (sketchy) assumptions about traffic

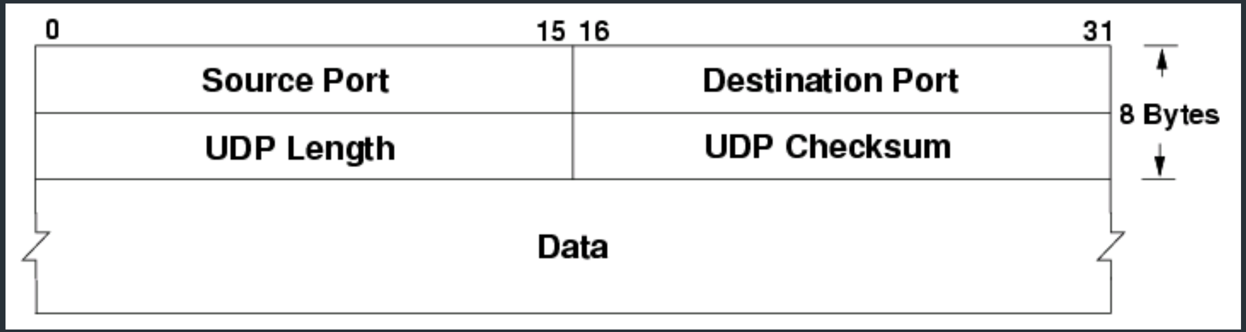
IP Header



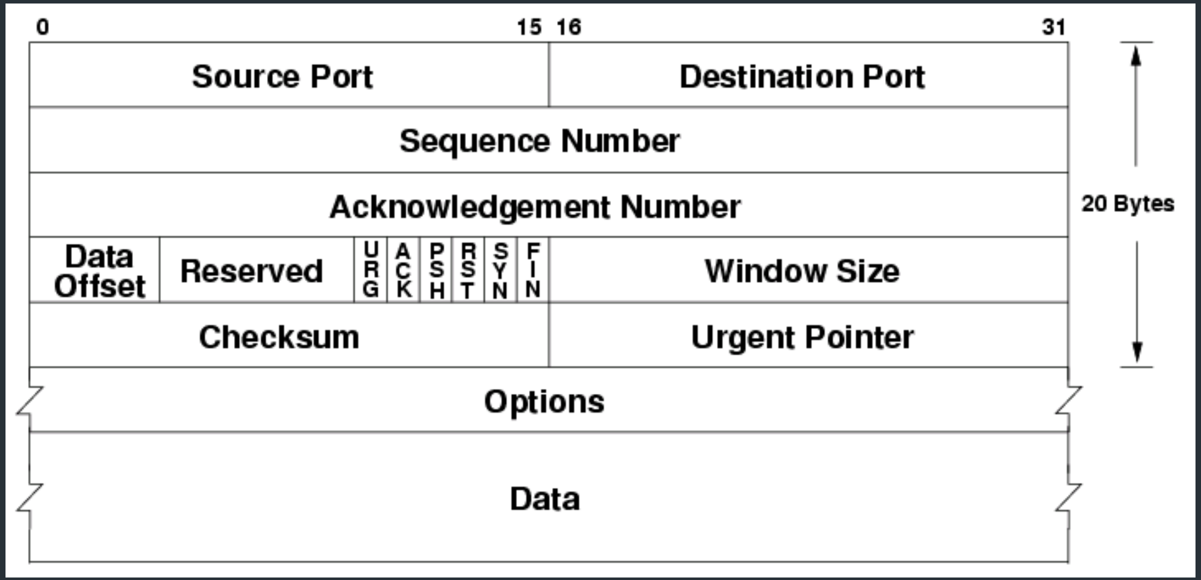
Where are the port numbers?????

… ports are actually part of the transport layer header!

UDP



TCP

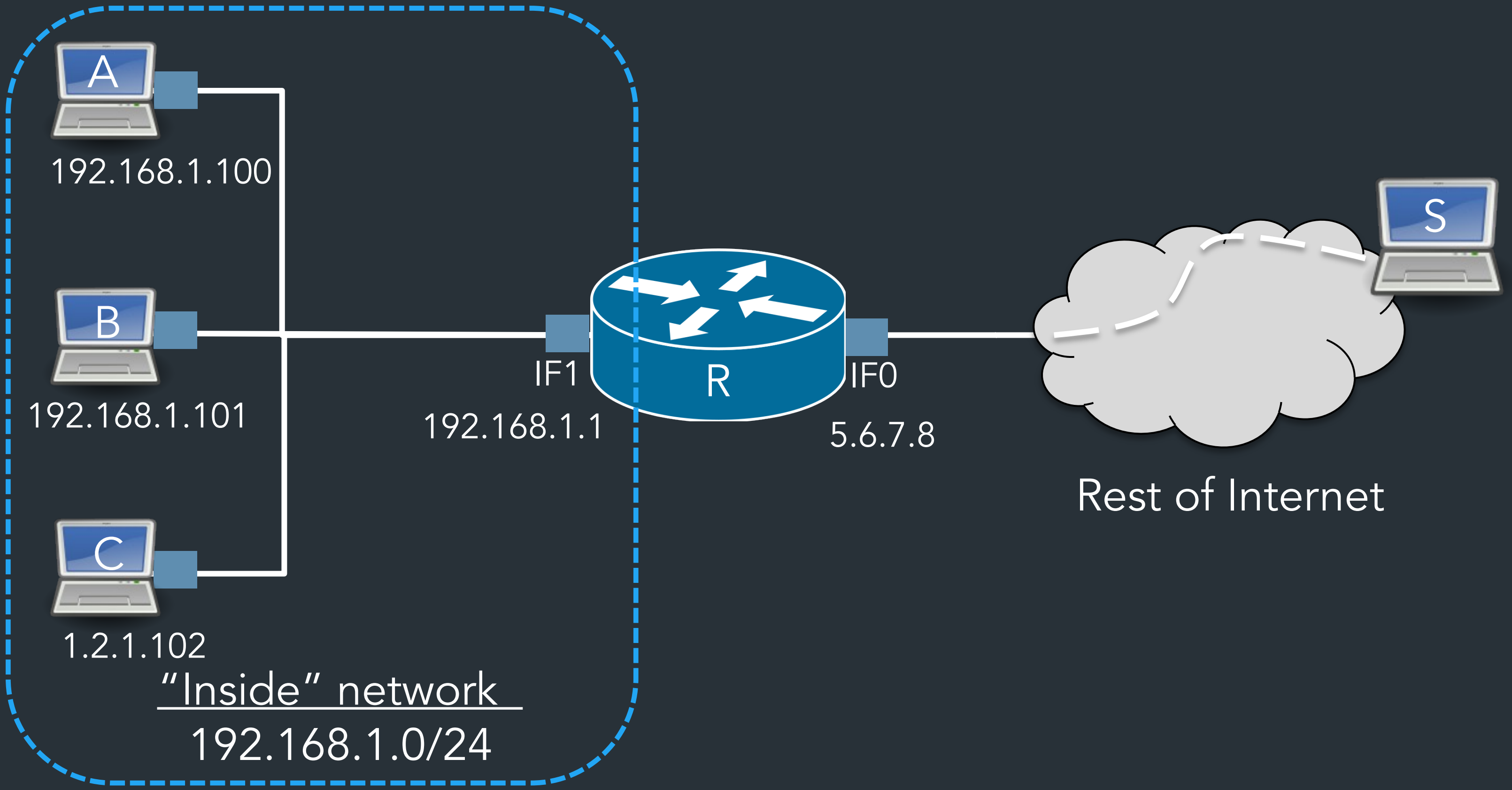


Problem?

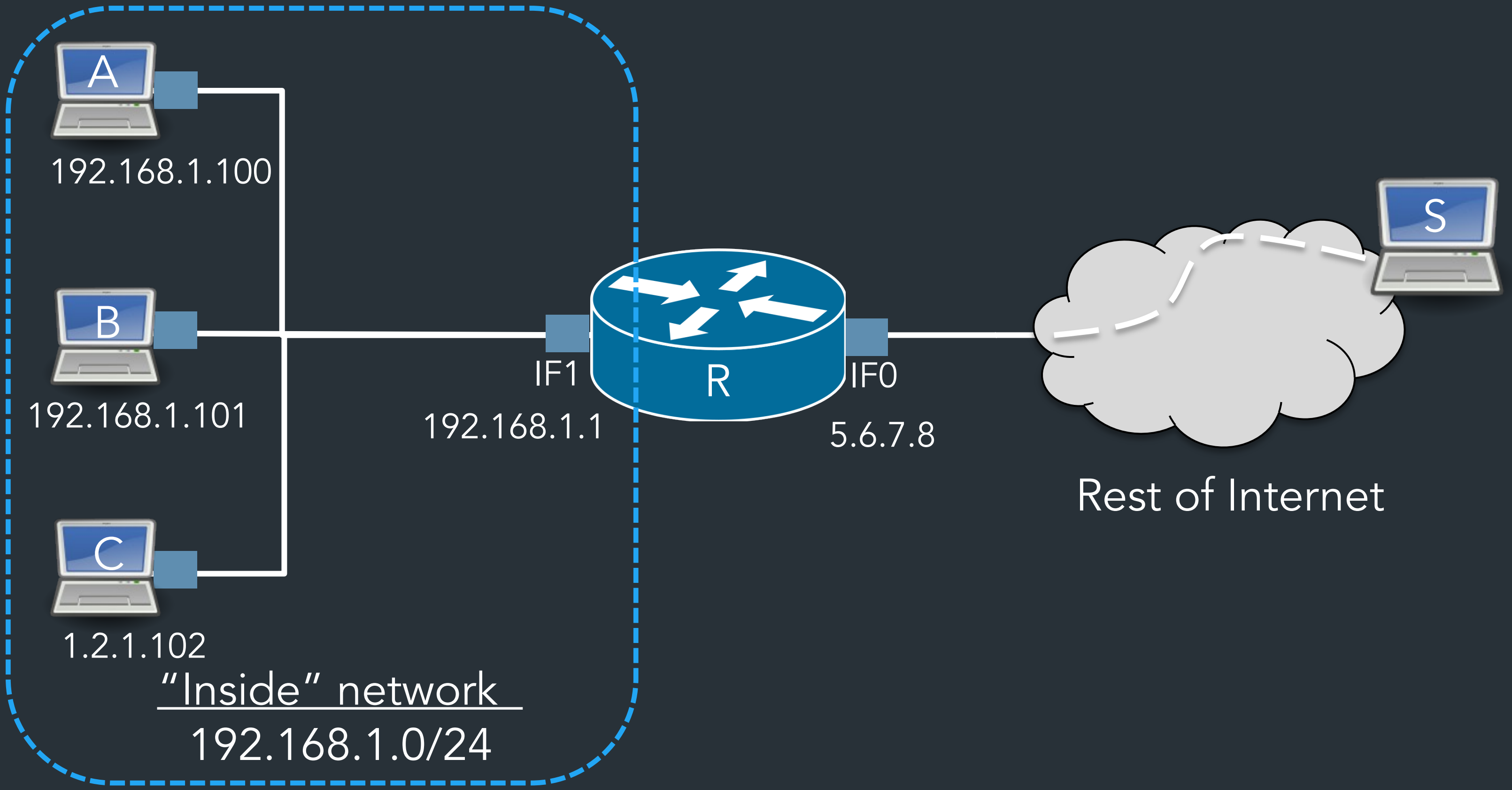
⇒ Technically a violation of layering! Network layer shouldn’t care about port numbers, but here it matters

⇒ NAT needs to know semantics of TCP/UDP (how connections start/end…

…but wait there’s more…



What happens when outside host S wants to connect to inside host A?



What happens when outside host S wants to connect to inside host A?

Can't do it (at least without special setup)!
⇒ By default, R only knows how to translate packets for connections originating from INSIDE the network
⇒ Breaks end to end connectivity!!!

Private IPs (RFC1918)

IP ranges reserved for "private" networks:

Prefix	Use
127.0.0.0/8	"Loopback" address—always for current host
10.0.0.0/8	Reserved for private internal networks (RFC1918)
192.168.0.0/16	
172.16.0.0/12	

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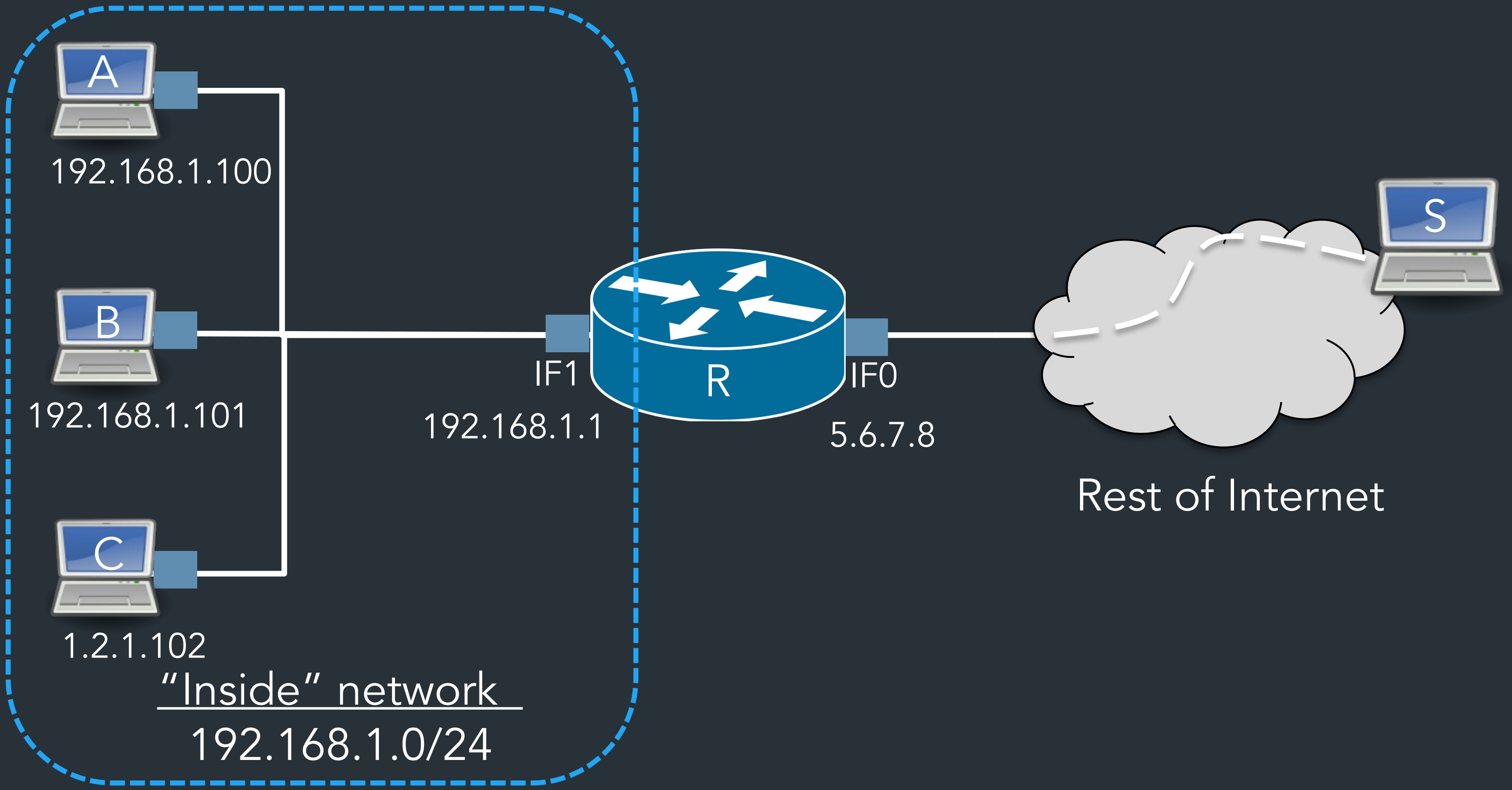
172.16.0.0/12	

- Many networks will use these blocks internally
- These IPs should never be routed over the Internet!
  - What would happen if they were?



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⇒ By default, R only knows how to translate packets for connections originating from INSIDE the network

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End to end connectivity, you say?

Why is this bad?

NAT is used in just about every consumer network

- Generally: can't connect directly to an end host unless it connects to you first

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- Need extra work for any protocols that need a direct connection between hosts

=> When do we need this?

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NAT is used in just about every consumer network

- Generally: can't connect directly to an end host unless it connects to you first

- Need extra work for any protocols that need a direct connection between hosts

$\Rightarrow$ Protocols that aren't strictly client-server
$\Rightarrow$ Latency critical applications: voice/video calls, games

NAT Traversal

Various methods, depending on the type of NAT

Examples:

- Manual method: port forwarding
- ICE: Interactive Connectivity Establishment (RFC8445)
- STUN: Session Traversal Utilities for NAT (RFC5389)

One idea: connect to external server via UDP, it tells you the address/port

NAT Example

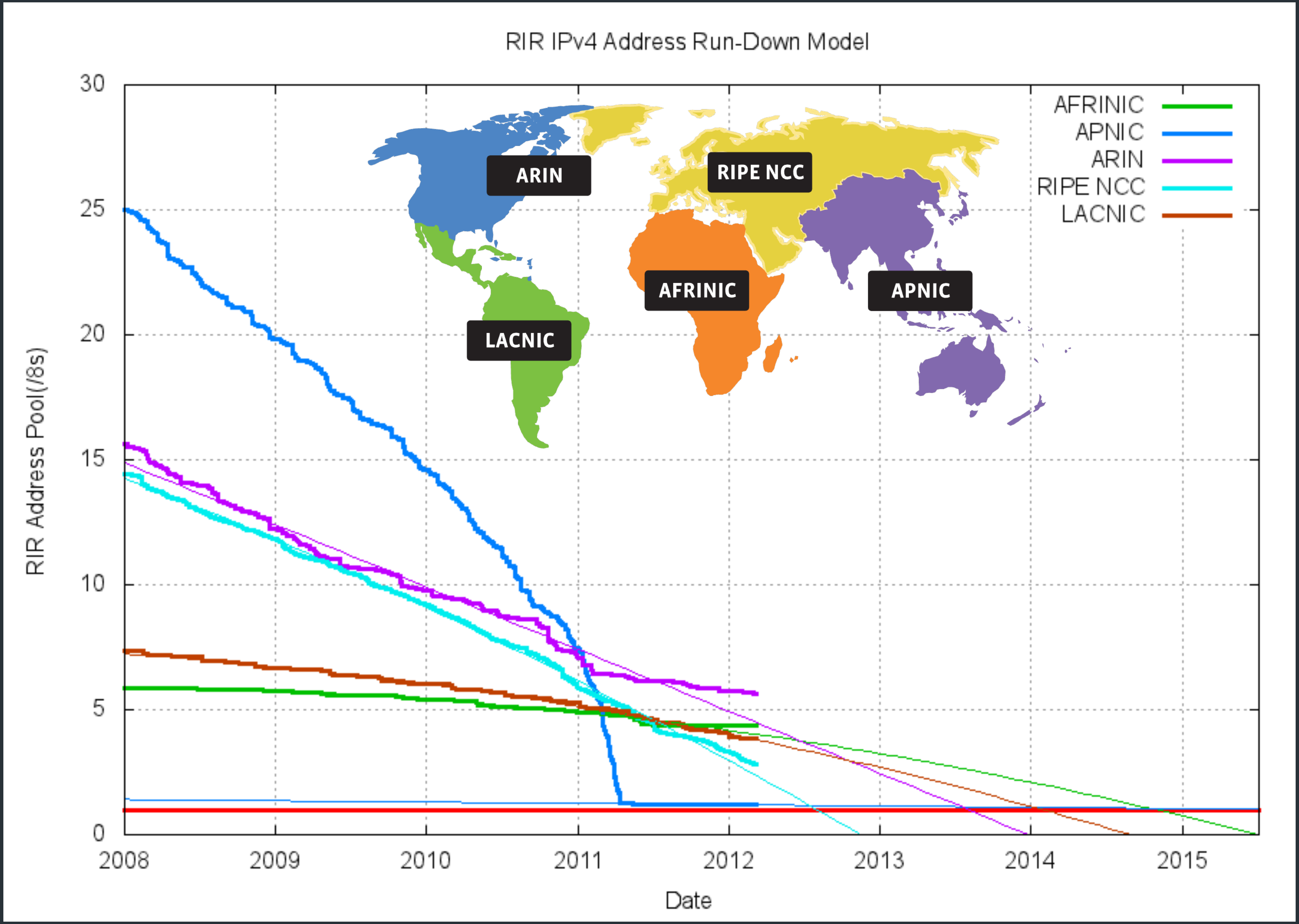
IPv6

IP challenge: Address space exhaustion

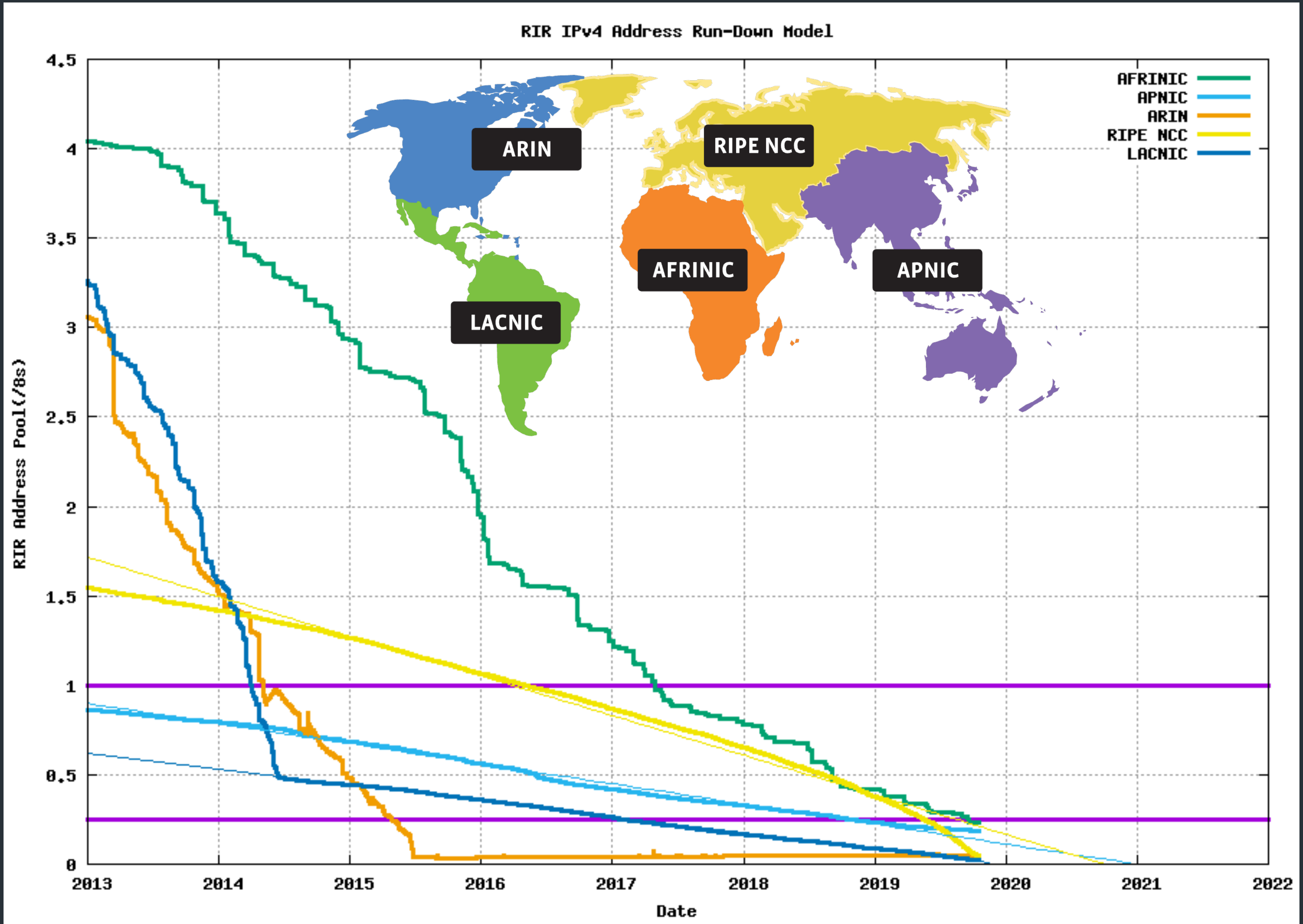
- IP version 4: ~4 billion IP addresses
  - World population: ~8 billion
  - Est. number of devices on Internet (2021): >10-30 billion

- Since 1990s: various tricks
  - Smarter allocations by registrars
  - Address sharing: Network Address Translation (NAT)
  - DHCP
  - Reclaiming unused space

- Long term solution: IP version 6

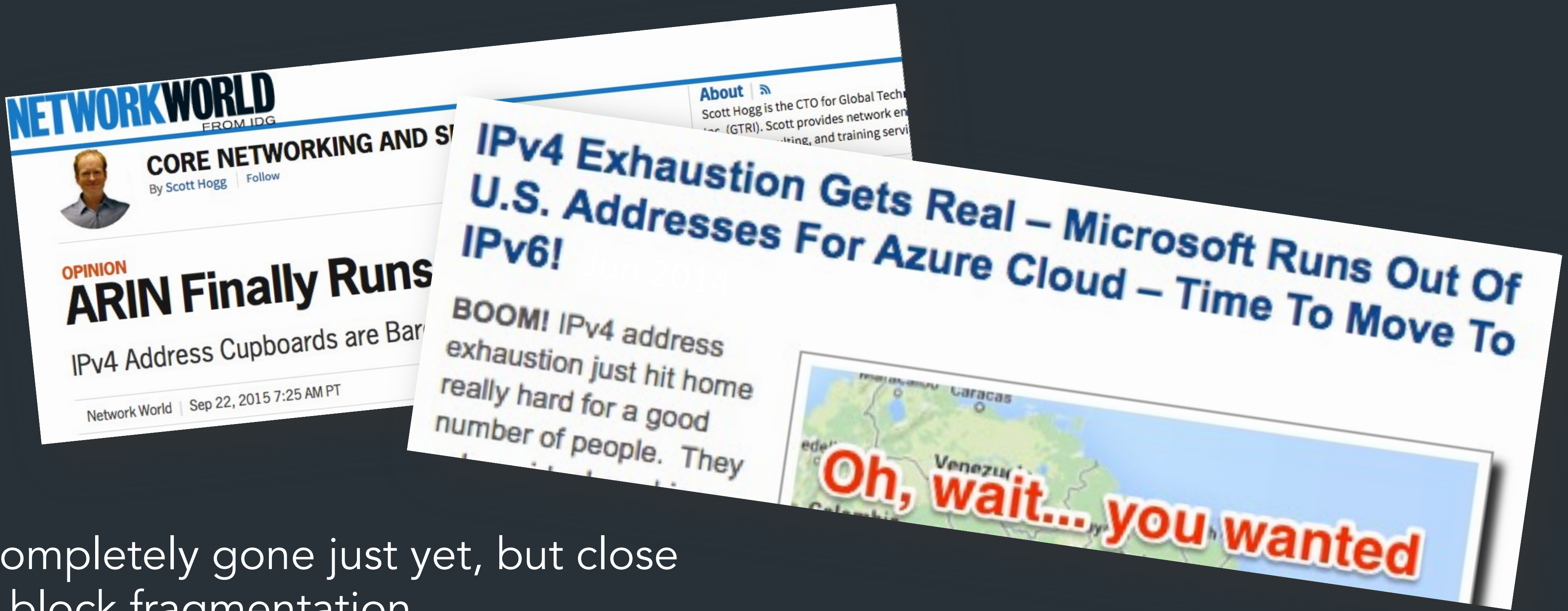


Source: potaroo.net/tools/ipv4



Source: potaroo.net/tools/ipv4

So what happened when we ran out of IPv4 addresses?

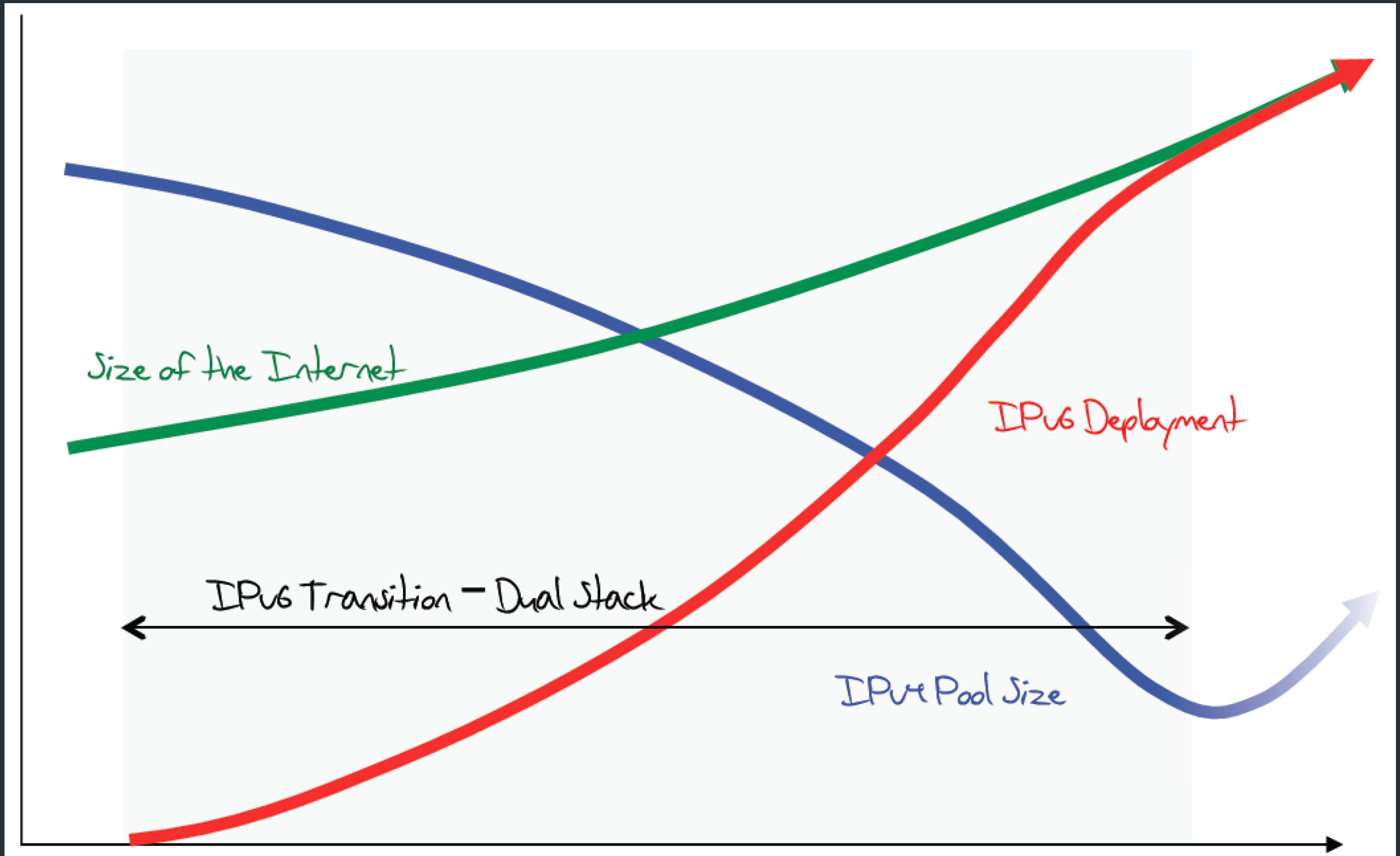


- It's not completely gone just yet, but close
- Address block fragmentation
  - Secondary market for IPv4
  - E.g., in 2011 Microsoft bought >600K US IPv4 addresses for $7.5M
- NATs galore
  - Home NATs, carrier-grade NATs

IPv6

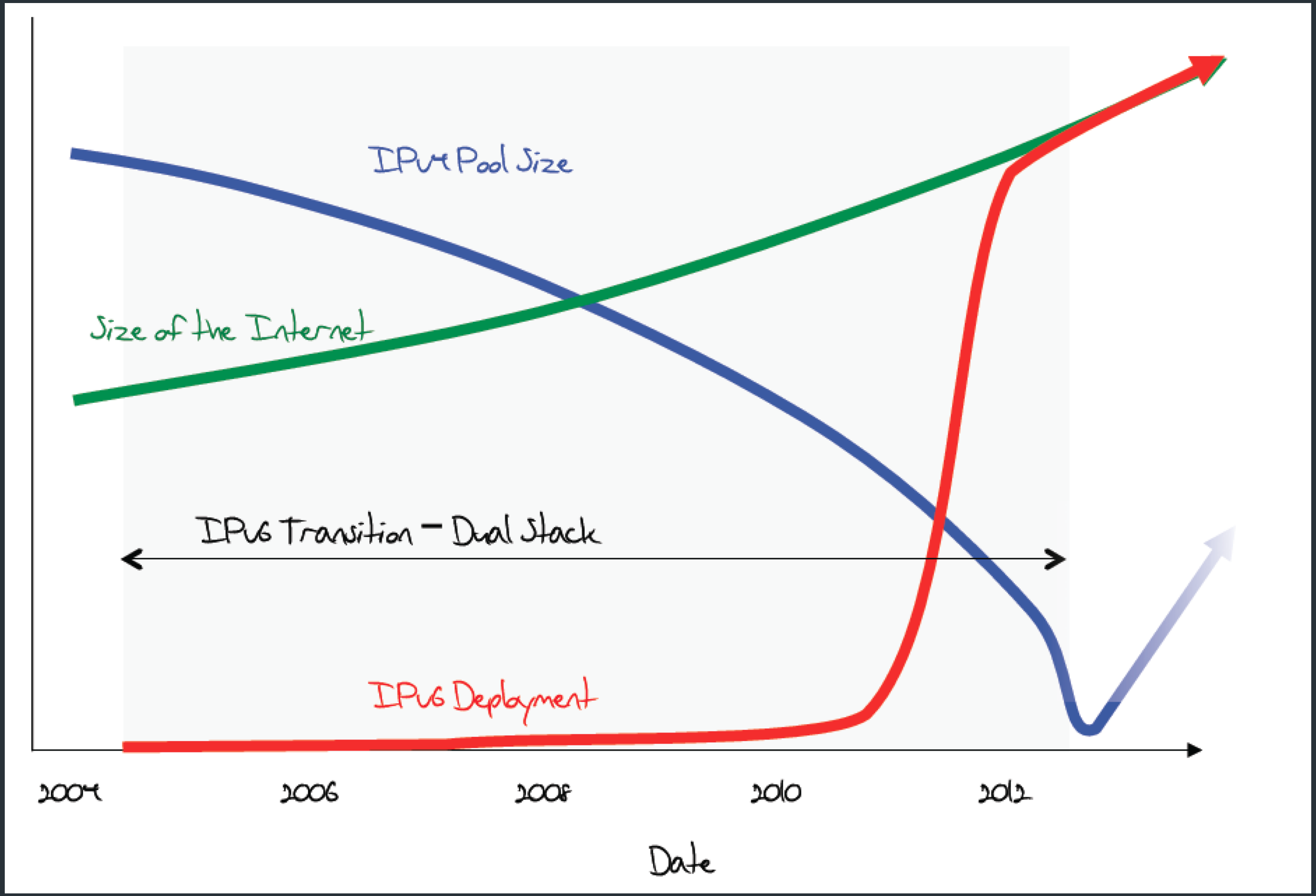
- Main motivation: IPv4 address exhaustion
- Initial idea: larger address space
- Need new packet format:
  - REALLY expensive to upgrade all infrastructure!
  - While at it, why don't we fix a bunch of things in IPv4?
- Work started in 1994, basic protocol published in 1998

The original expected plan

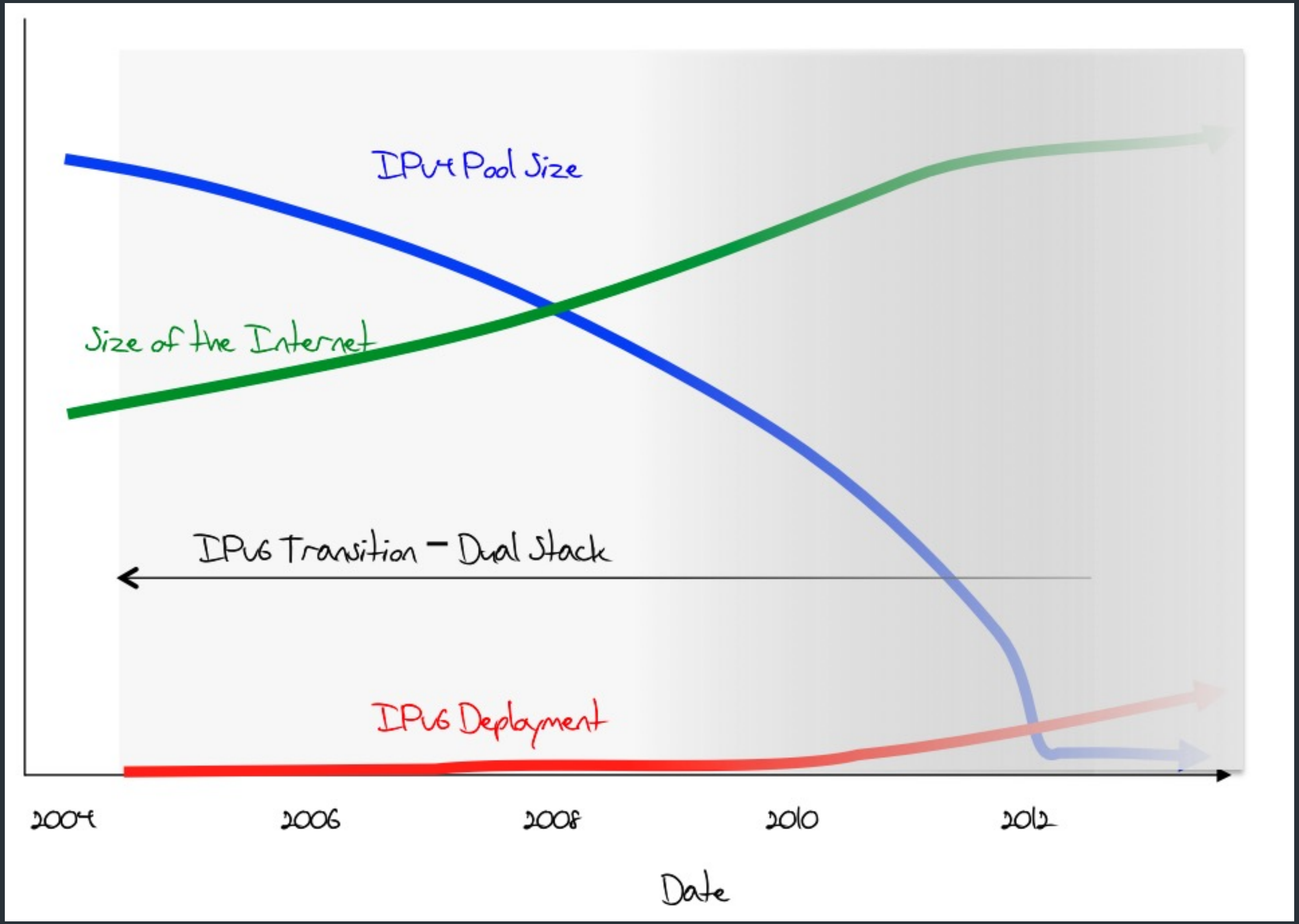


From: http://www.potaroo.net/ispcol/2012-08/EndPt2.html

The plan in 2011



What was happening (late 2012)



June 6th, 2012

WORLD
IPv6
LAUNCH

Transition is not painless

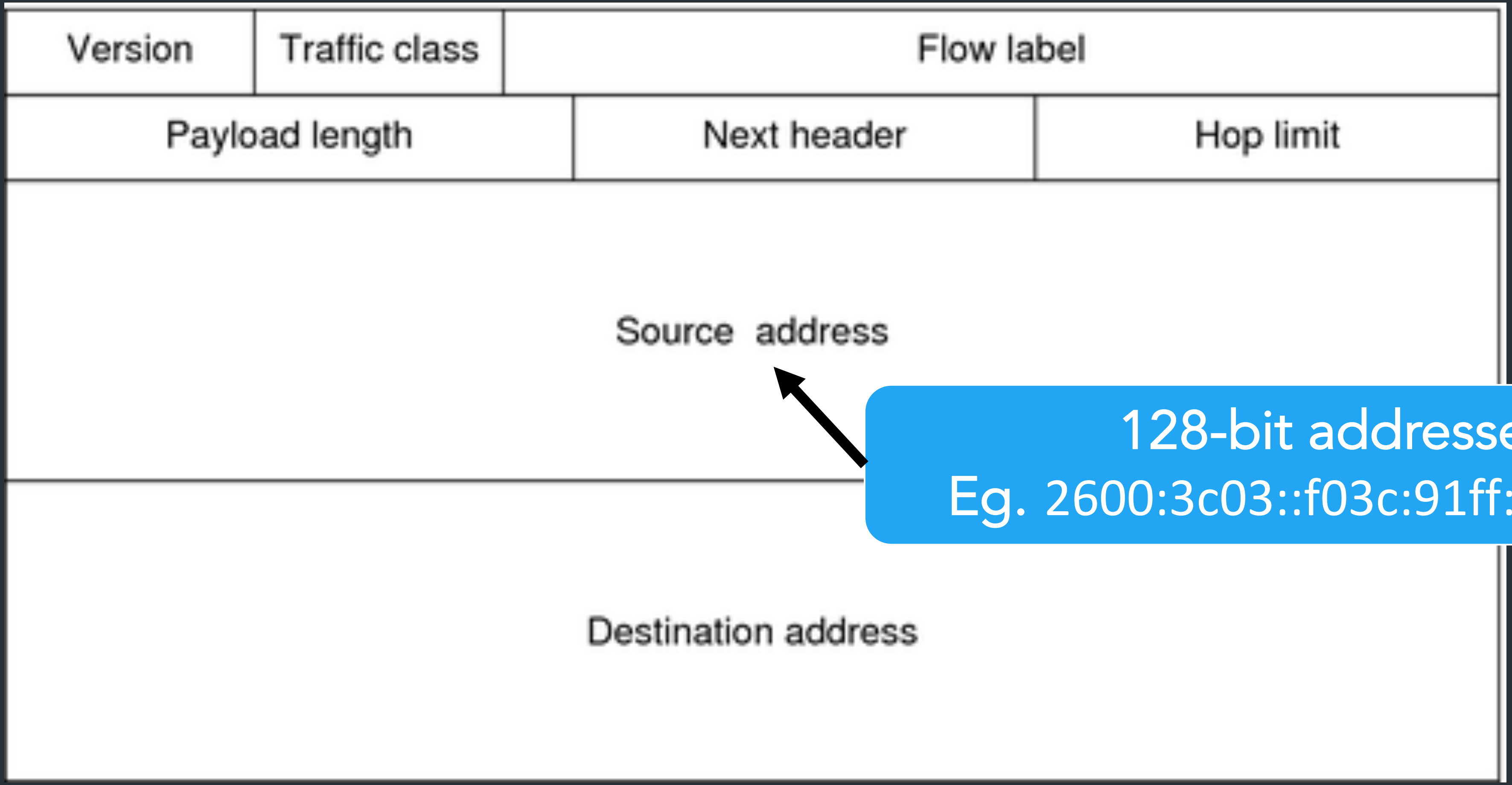
From http://www.internetsociety.org/deploy360/ipv6/ :

You may want to begin with our "**Where Do I Start?**" page where we have guides for:

- **Network operators**
- **Developers**
- **Content providers / website owners**
- **Enterprise customers**
- **Domain name registrars**
- **Consumer electronics vendors**
- **Internet exchange point (IXP) operators**

- Why do each of these parties have to do something?

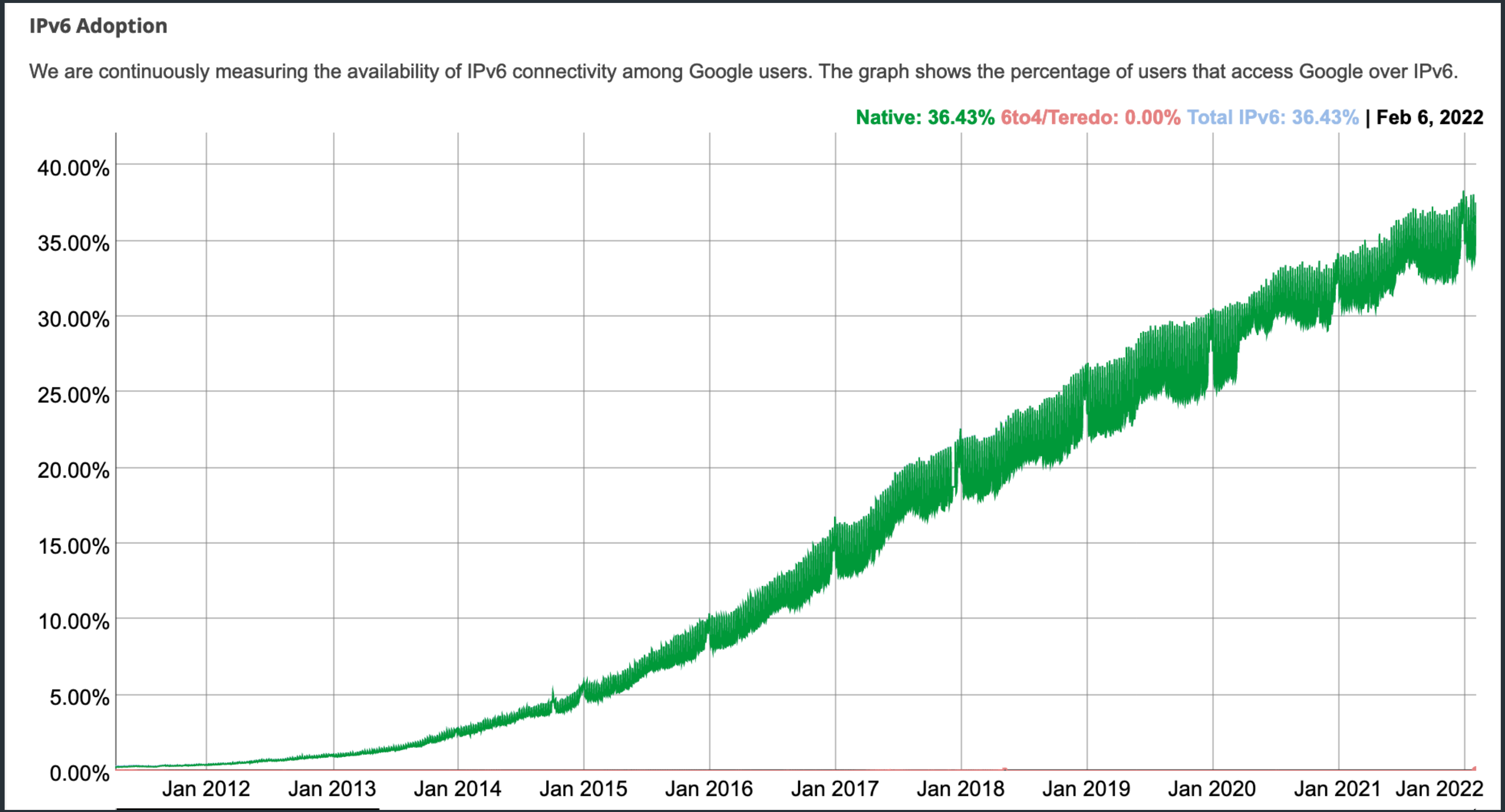
IP version 6



128-bit addresses!
Eg. 2600:3c03::f03c:91ff:fe6e:e3e1

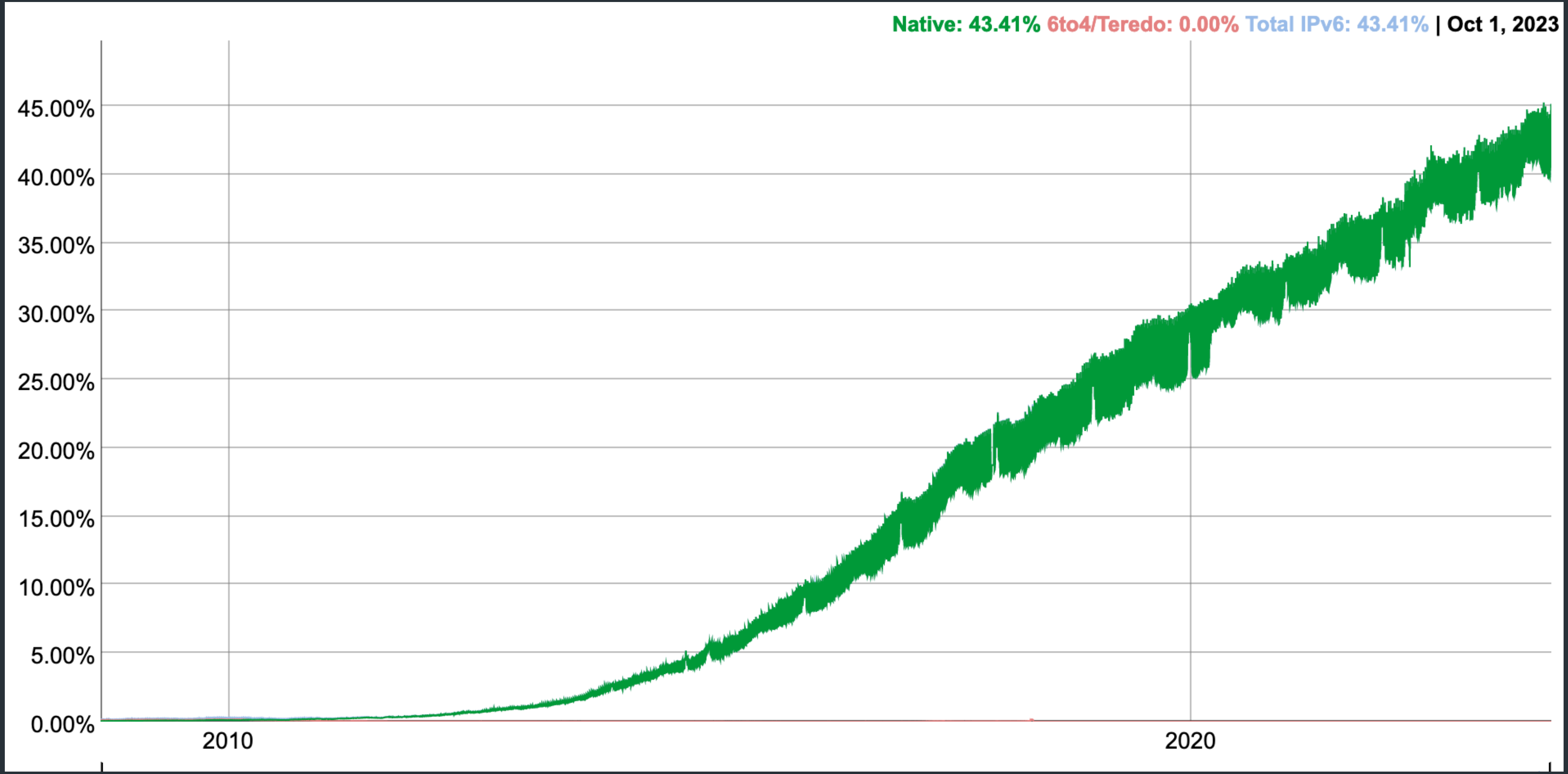
IPv6 Adoption

At Google:

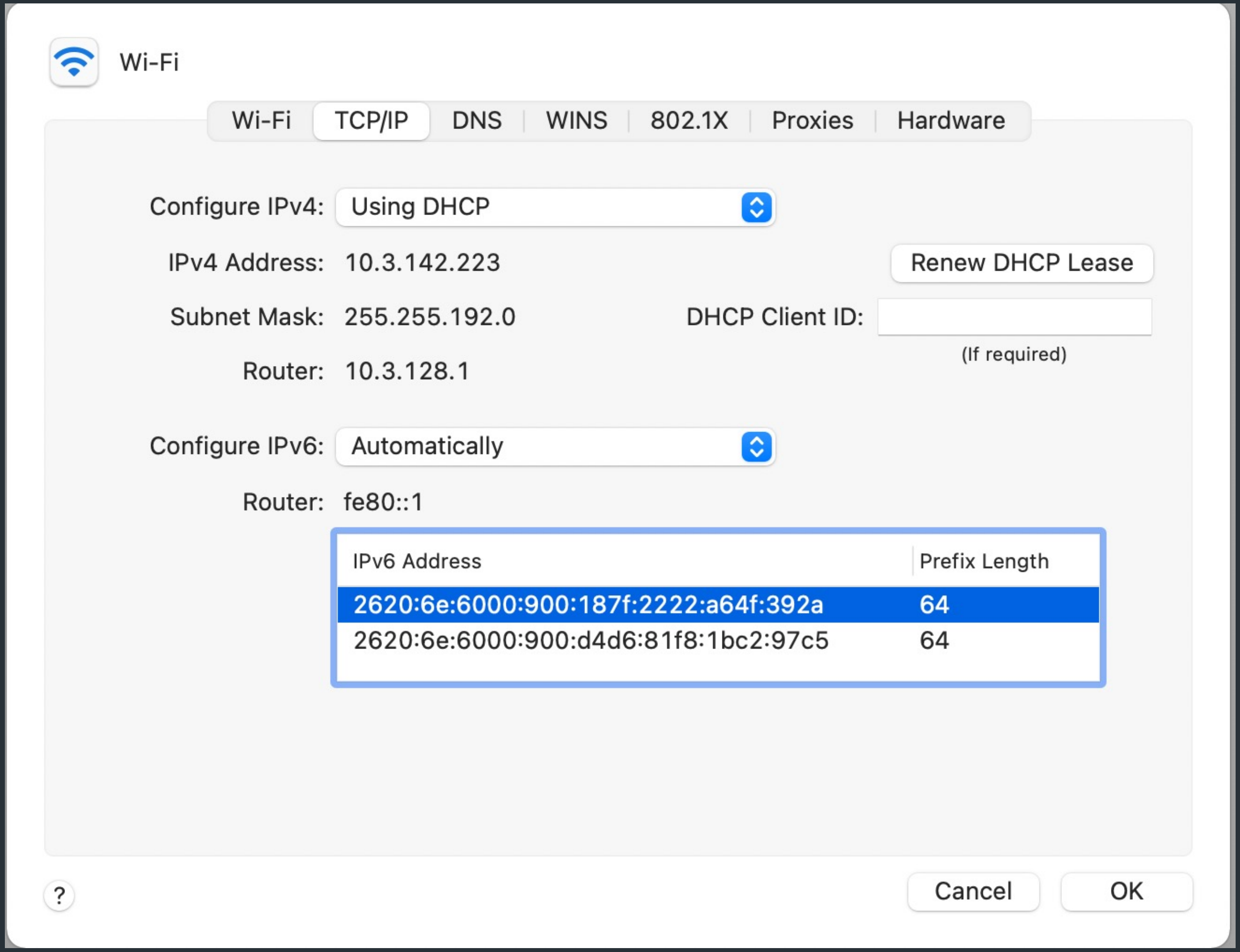


IPv6 Adoption

At Google:



At Brown


Wi-Fi
Wi-Fi
TCP/IP
DNS
WINS
802.1X
Proxies
Hardware
Configure IPv4:
Using DHCP
IPv4 Address:
10.3.142.223
Renew DHCP Lease
Subnet Mask:
255.255.192.0
DHCP Client ID:
(If required)
Router:
10.3.128.1
Configure IPv6:
Automatically
Router:
fe80::1
IPv6 Address
Prefix Length
2620:6e:6000:900:187f:2222:a64f:392a
64
2620:6e:6000:900:d4d6:81f8:1bc2:97c5
64
?
Cancel
OK

IPv6 Key Features

- 128-bit addresses
- Simplifies basic packet format through *extension headers*
  - 40-byte base header (fixed)
  - Make less common fields optional
- Security and Authentication

IPv6 Address Representation

- Groups of 16 bits in hex notation

  47cd:1244:3422:0000:0000:fef4:43ea:0001

- Two rules:
  - Leading 0's in each 16-bit group can be omitted

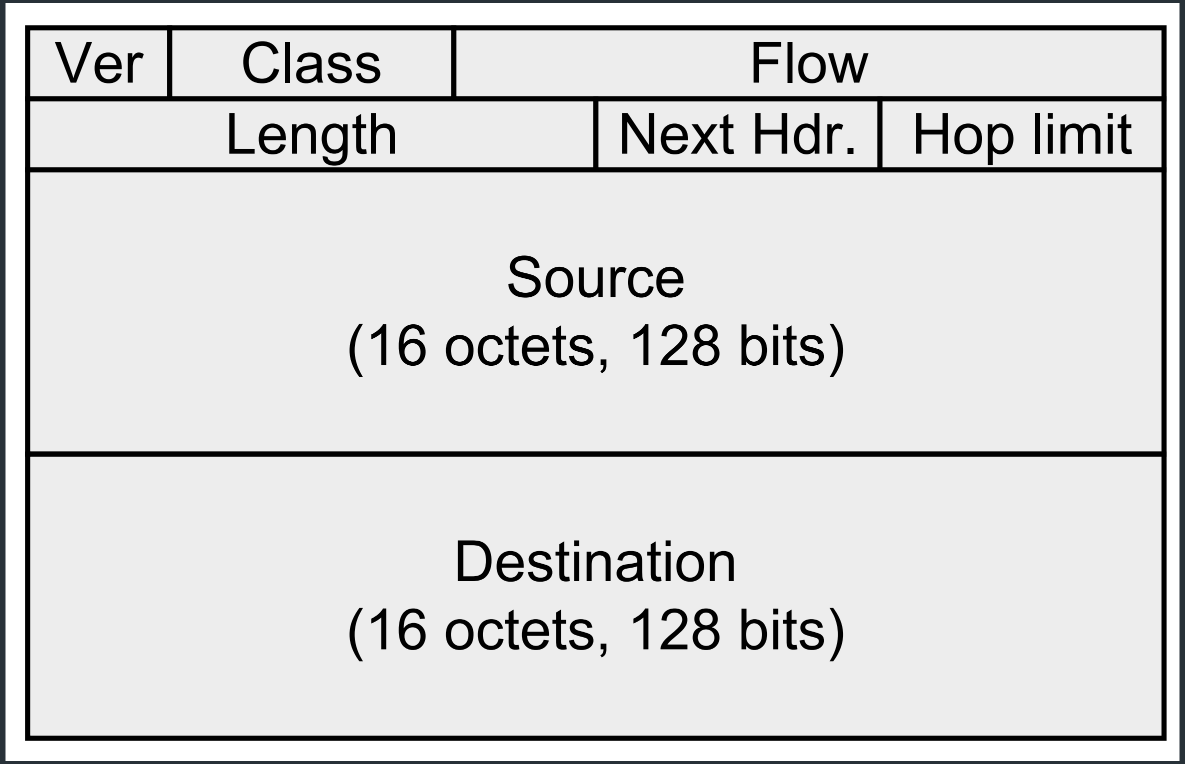
    47cd:1244:3422:0:0:fef4:43ea:1
  - One contiguous group of 0's can be compacted

    47cd:1244:3422::fef4:43ea:1

IPv6 Addresses

- Break 128 bits into 64-bit network and 64-bit interface
  - Makes autoconfiguration easy: interface part can be derived from Ethernet address, for example
- Types of addresses
  - All 0's: unspecified
  - 000…1: loopback
  - ff/8: multicast
  - fe8/10: link local unicast
  - fec/10: site local unicast
  - All else: global unicast

IPv6 Header



Ver
Class
Flow
Length
Next Hdr.
Hop limit
Source
(16 octets, 128 bits)
Destination
(16 octets, 128 bits)

IPv6 Header Fields

- Version: 4 bits, 6
- Class: 8 bits, like TOS in IPv4
- Flow: 20 bits, identifies a *flow*
- Length: 16 bits, datagram length
- Next Header, 8 bits: …
- Hop Limit: 8 bits, like TTL in IPv4
- Addresses: 128 bits
- What’s missing?
  - No options, no fragmentation flags, *no checksum*

Design Philosophy

- Simplify handling
  - New option mechanism (fixed size header)
  - No more header length field
- Do less work at the network (why?)
  - No fragmentation
  - No checksum
- General flow label
  - No semantics specified
  - Allows for more flexibility
- Still no accountability

With some content from Scott Shenker

Interoperability

- RFC 4038
  - Every IPv4 address has an associated IPv6 address (mapped)
  - Networking stack translates appropriately depending on other end
  - Simply prefix 32-bit IPv4 address with 80 bits of 0 and 16 bits of 1:
  - E.g., ::FFFF:128.148.32.2
- Two IPv6 endpoints must have IPv6 stacks
- Transit network:
  - v6 – v6 – v6 : ✓
  - v4 – v4 – v4 : ✓
  - v4 – v6 – v4 : ✓
  - v6 – v4 – v6 : ✗!!

Example Next Header Values

- 0: Hop by hop header
- 1: ICMPv4
- 4: IPv4
- 6:TCP
- 17: UDP
- 41: IPv6
- 43: Routing Header
- 44: Fragmentation Header
- 58: ICMPv6

Current State

- IPv6 Deployment picking up
- Most end hosts have dual stacks today (Windows, Mac OSX, Linux, *BSD, Solaris)
- Requires all parties to work!
  - Servers, Clients, DNS, ISPs, all routers
- IPv4 and IPv6 will coexist for a long time

Coming Up

- Routing: how do we fill the routing tables?
  - Intra-domain routing: Tuesday, 10/4
  - Inter-domain routing: Thursday, 10/6

Example

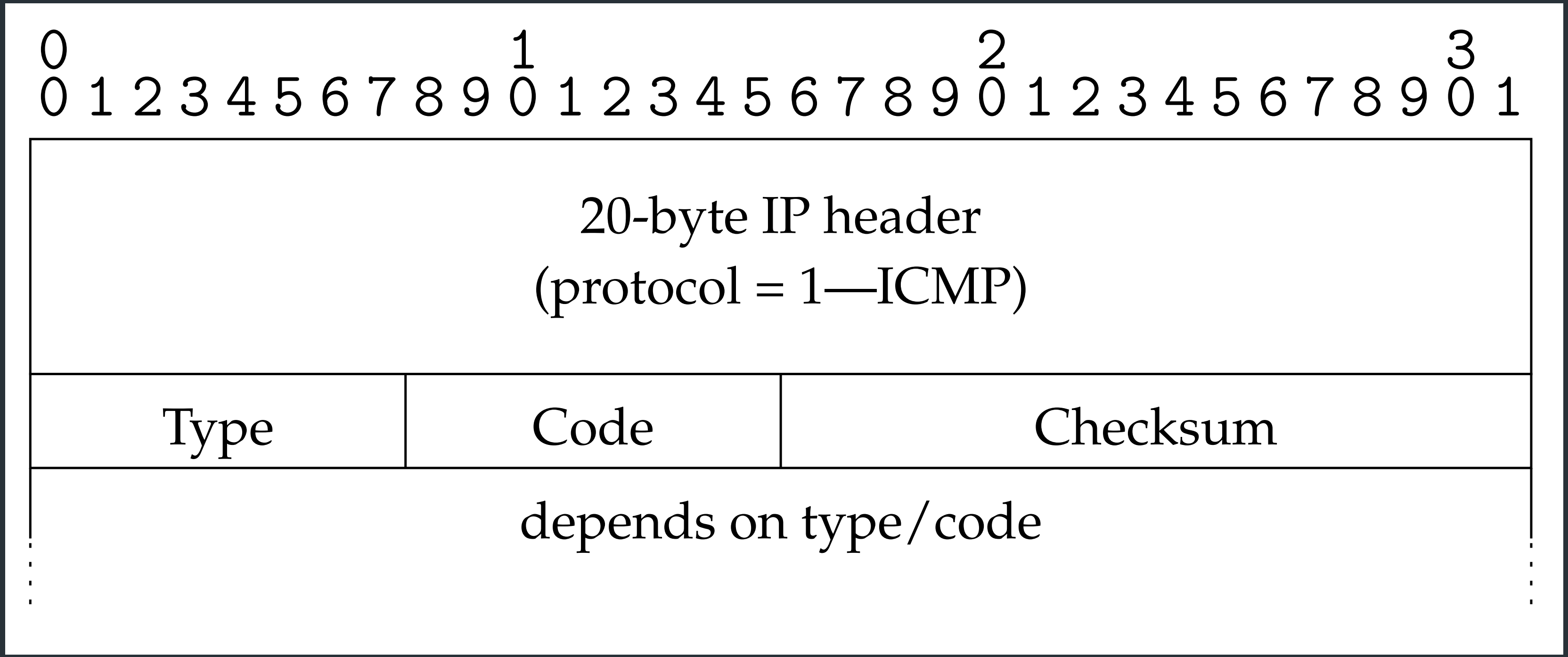
```
# arp -n
Address                  HWtype  HWaddress           Flags Mask            Iface
172.17.44.1              ether   00:12:80:01:34:55   C                     eth0
172.17.44.25             ether   10:dd:b1:89:d5:f3   C                     eth0
172.17.44.6              ether   b8:27:eb:55:c3:45   C                     eth0
172.17.44.5              ether   00:1b:21:22:e0:22   C                     eth0
```

```
# ip route
127.0.0.0/8 via 127.0.0.1 dev lo
172.17.44.0/24 dev enp7s0  proto kernel  scope link  src 172.17.44.22  metric 204
default via 172.17.44.1 dev eth0 src 172.17.44.22  metric 204
```

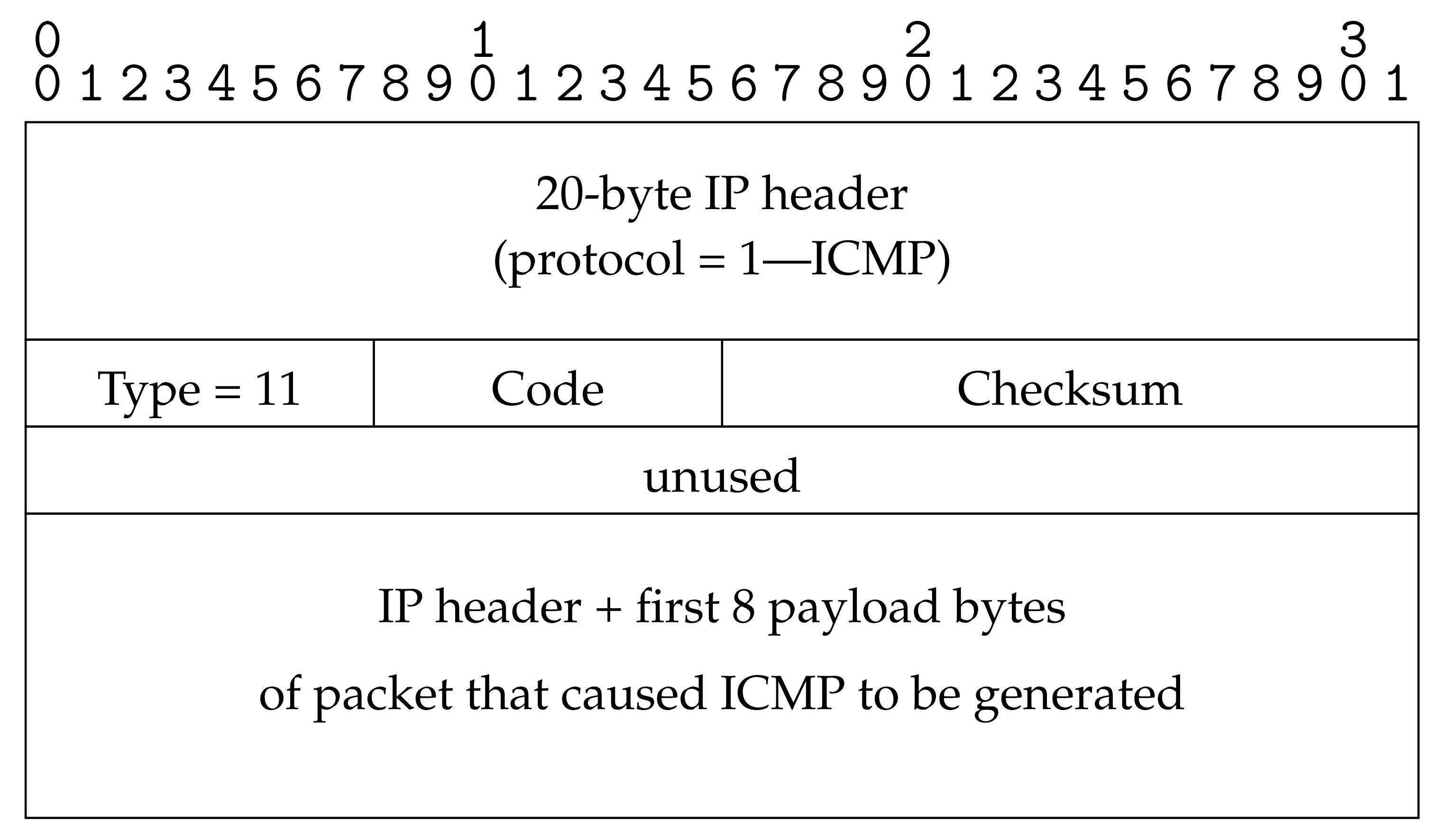
Internet Control Message Protocol (ICMP)

- Echo (ping)
- Redirect
- Destination unreachable (protocol, port, or host)
- TTL exceeded
- Checksum failed
- Reassembly failed
- Can't fragment
- Many ICMP messages include part of packet that triggered them
- See http://www.iana.org/assignments/icmp-parameters

ICMP message format



Example: Time Exceeded



- Code usually 0 (TTL exceeded in transit)
- Discussion: traceroute